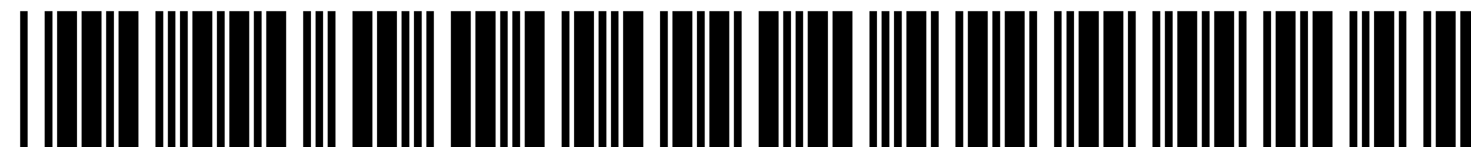

(12) **United States Patent**
Yamazawa

(10) **Patent No.: US 9,953,811 B2**
(45) **Date of Patent: Apr. 24, 2018**

(54) **PLASMA PROCESSING METHOD**

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(72) Inventor: **Yohei Yamazawa**, Nirasaki (JP)

(73) Assignee: **TOKYO ELECTRON LIMITED**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 863 days.

(21) Appl. No.: **14/325,457**

(22) Filed: **Jul. 8, 2014**

(65) **Prior Publication Data**

US 2015/0014276 A1 Jan. 15, 2015

Related U.S. Application Data

(62) Division of application No. 13/434,802, filed on Mar. 29, 2012, now abandoned.

(Continued)

(30) **Foreign Application Priority Data**

Mar. 29, 2011 (JP) 2011-072582

(51) **Int. Cl.**

H01L 21/306 (2006.01)
C23C 16/00 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***H01J 37/32697*** (2013.01); ***H01J 37/02*** (2013.01); ***H01J 37/321*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC H01J 37/321; H01J 37/3211; H01J 37/32119; H01J 37/32128;

(Continued)

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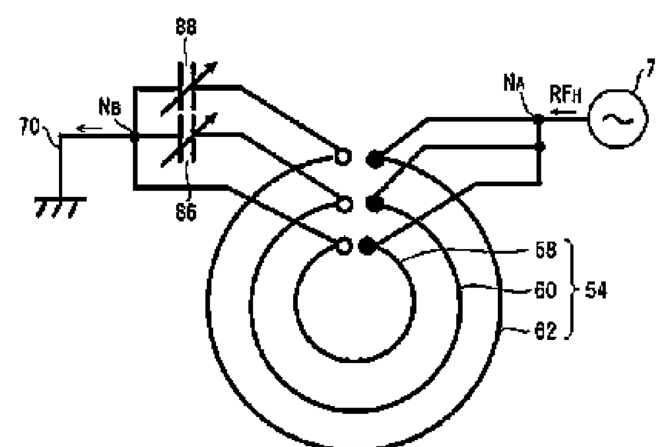
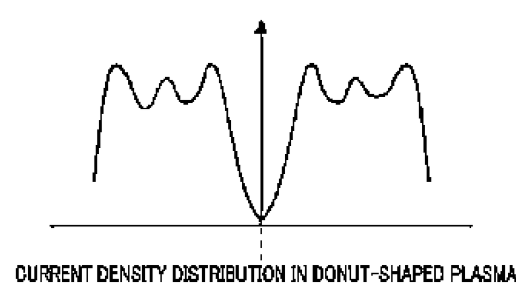
Primary Examiner — Luz L Alejandro Mulero
(74) *Attorney, Agent, or Firm* — Brundidge & Stanger, P.C.

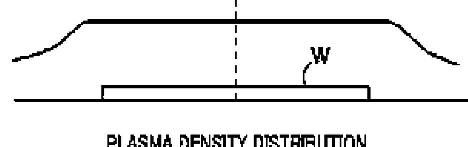
(57) **ABSTRACT**

A plasma processing method for performing a plasma process on a processing target substrate is provided. The plasma processing method includes: segmenting a RF antenna into an inner coil, an intermediate coil, and an outer coil with gaps therebetween in a radial direction, respectively, the inner coil, the intermediate coil and the outer coil being electrically connected to one another in parallel between a first node and a second node; providing a variable intermediate capacitor and a variable outer capacitor between the first node and the second node, the variable intermediate capacitor being electrically connected in series to the intermediate coil, the variable outer capacitor being electrically connected in series to the outer coil, no reactance device being connected to the inner coil; and controlling plasma density distribution on the processing target substrate by selecting or variably adjusting electrostatic capacitances of the intermediate capacitor and the outer capacitor.

9 Claims, 10 Drawing Sheets







Related U.S. Application Data

(60) Provisional application No. 61/472,671, filed on Apr. 7, 2011.

(51) **Int. Cl.**
H01J 37/32 (2006.01)
H01J 37/02 (2006.01)

(52) **U.S. Cl.**
CPC ***H01J 37/3211*** (2013.01); ***H01J 37/3244*** (2013.01); ***H01J 37/32119*** (2013.01); ***H01J 37/32137*** (2013.01); ***H01J 37/32174*** (2013.01); *H01J 2237/327* (2013.01); *H01J 2237/3341* (2013.01)

(58) **Field of Classification Search**
CPC H01J 37/32137; H01J 37/32146; H01J 37/32155; H01J 37/32165; H01J 37/32174; H01J 37/32183
USPC ...... 118/723 I, 723 IR, 723 AN; 156/345.48, 156/345.49; 315/111.51
See application file for complete search history.

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FIG. 1

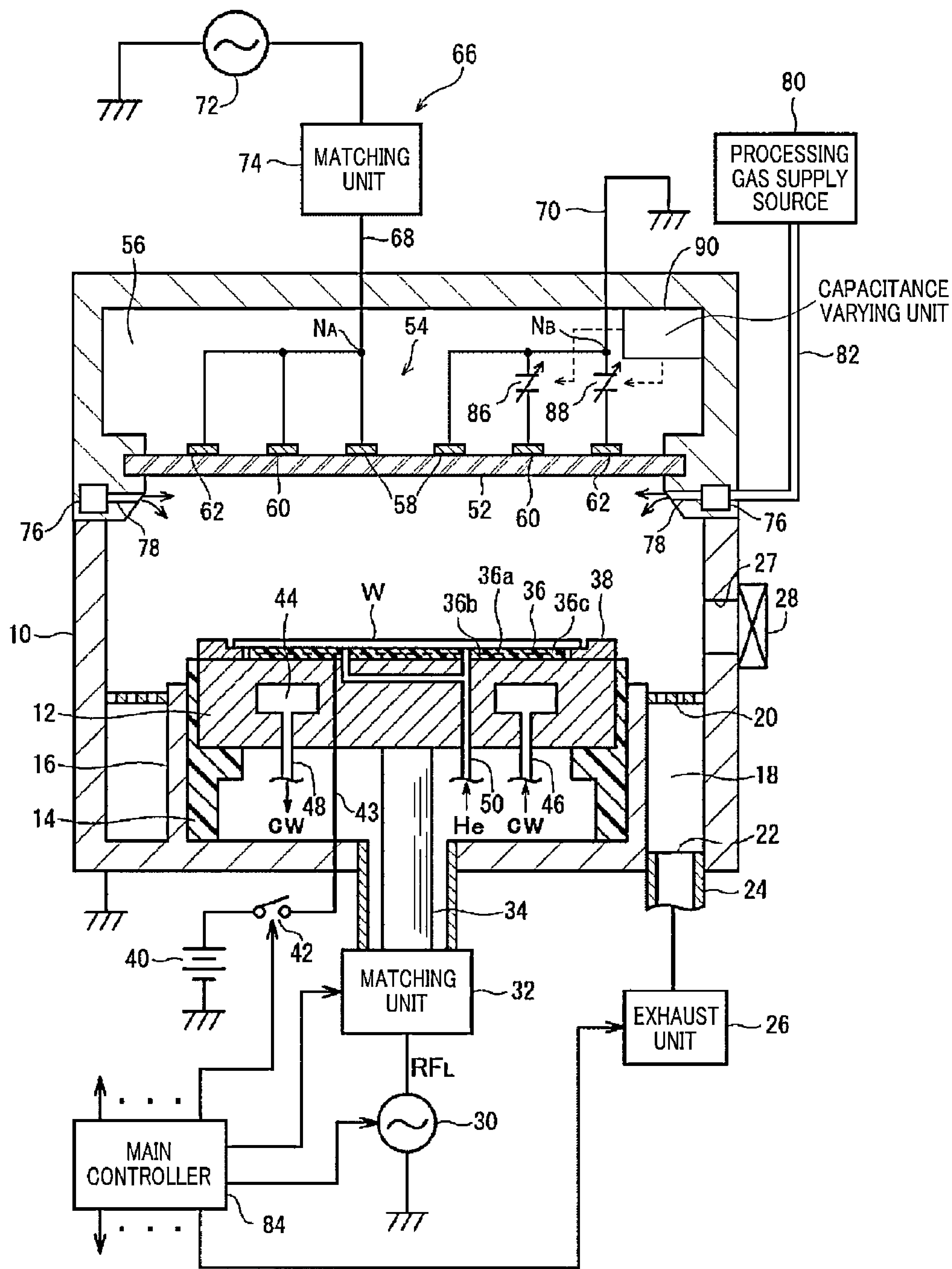


FIG. 2

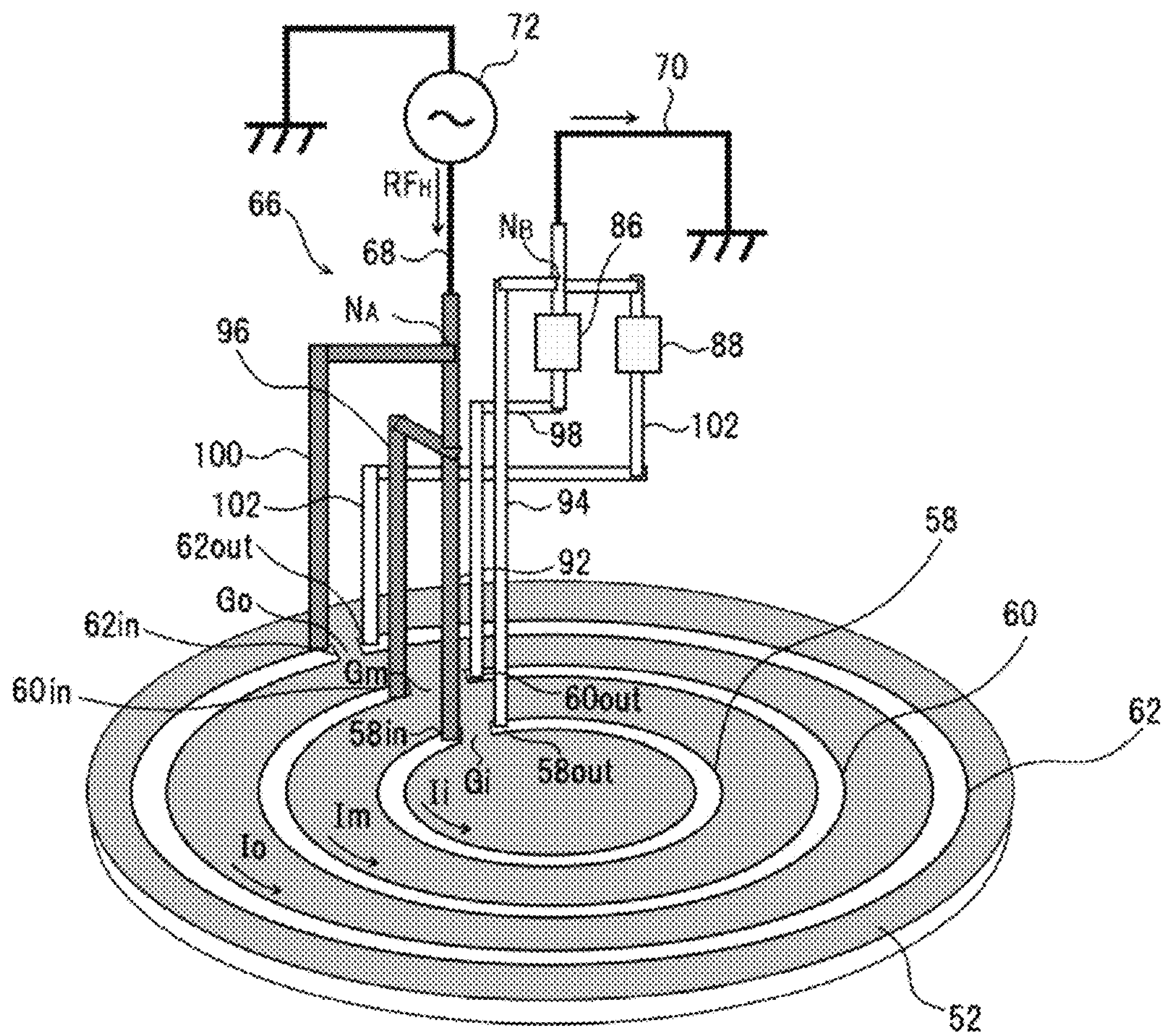
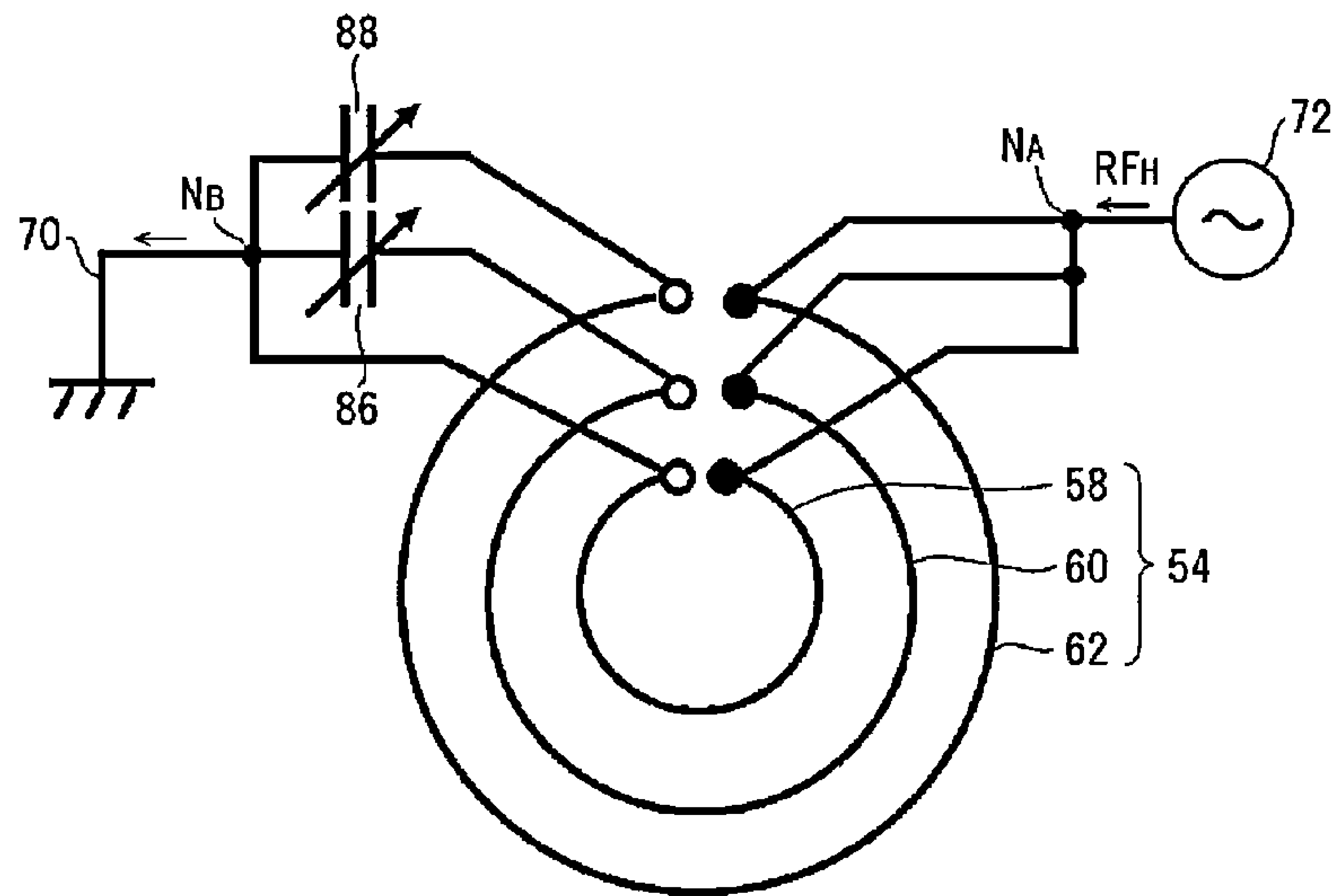
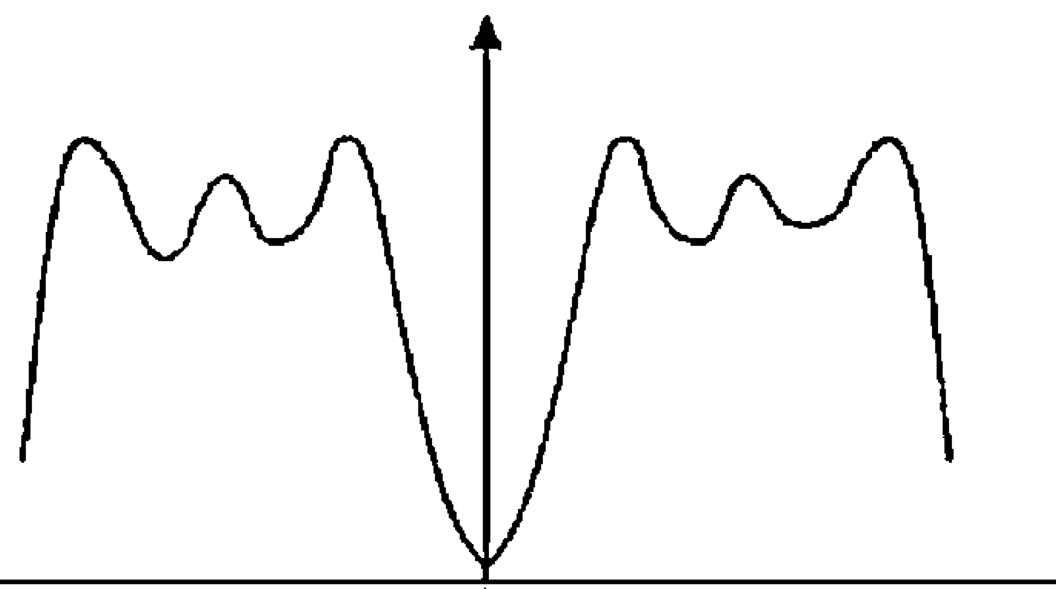
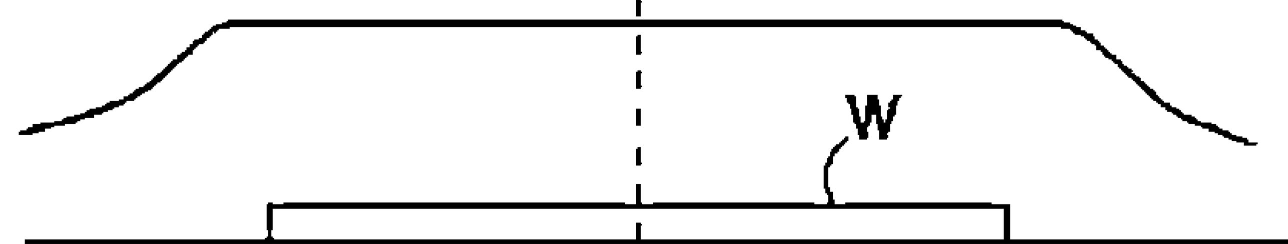


FIG. 3



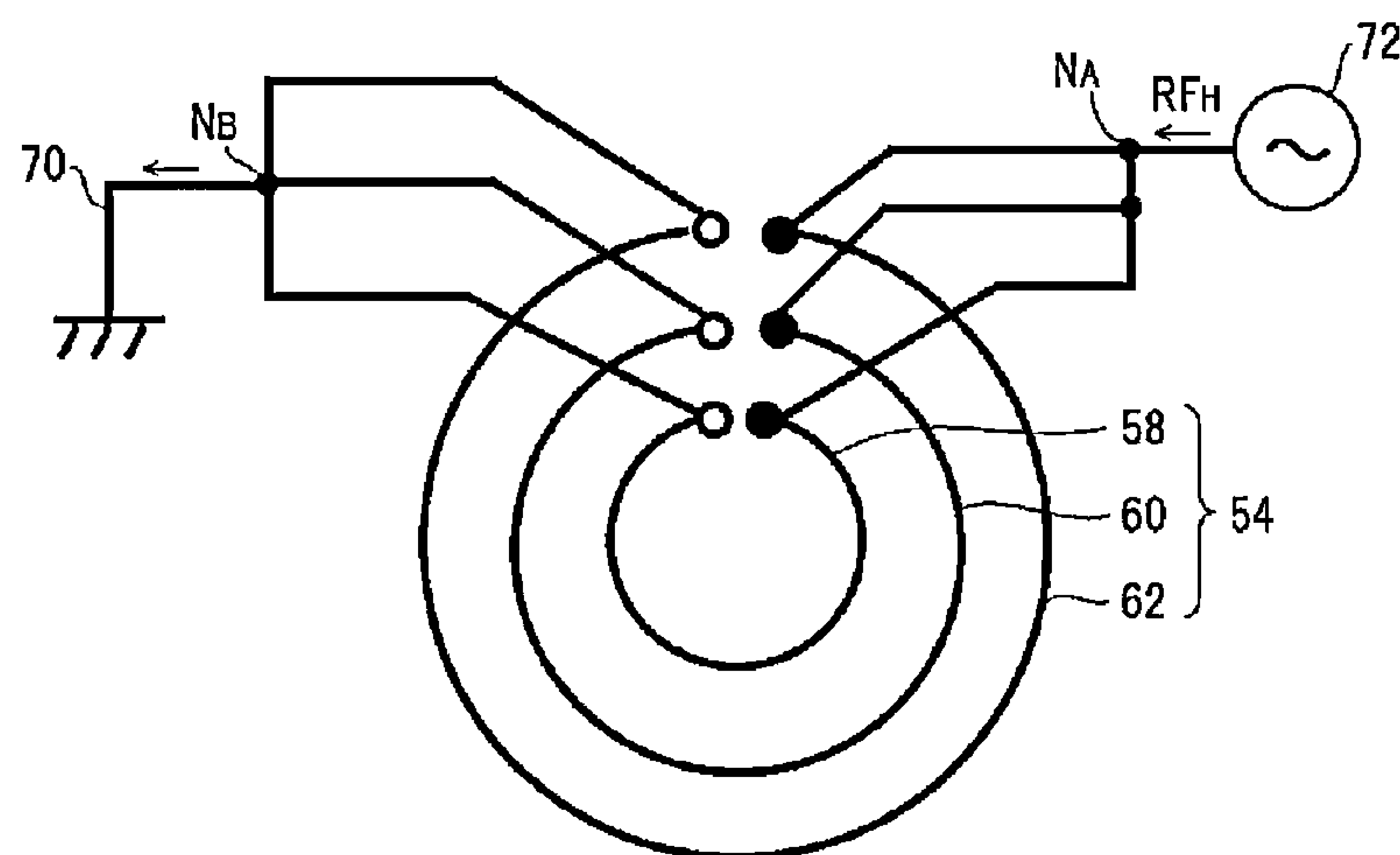


CURRENT DENSITY DISTRIBUTION IN DONUT-SHAPED PLASMA



PLASMA DENSITY DISTRIBUTION

FIG. 4



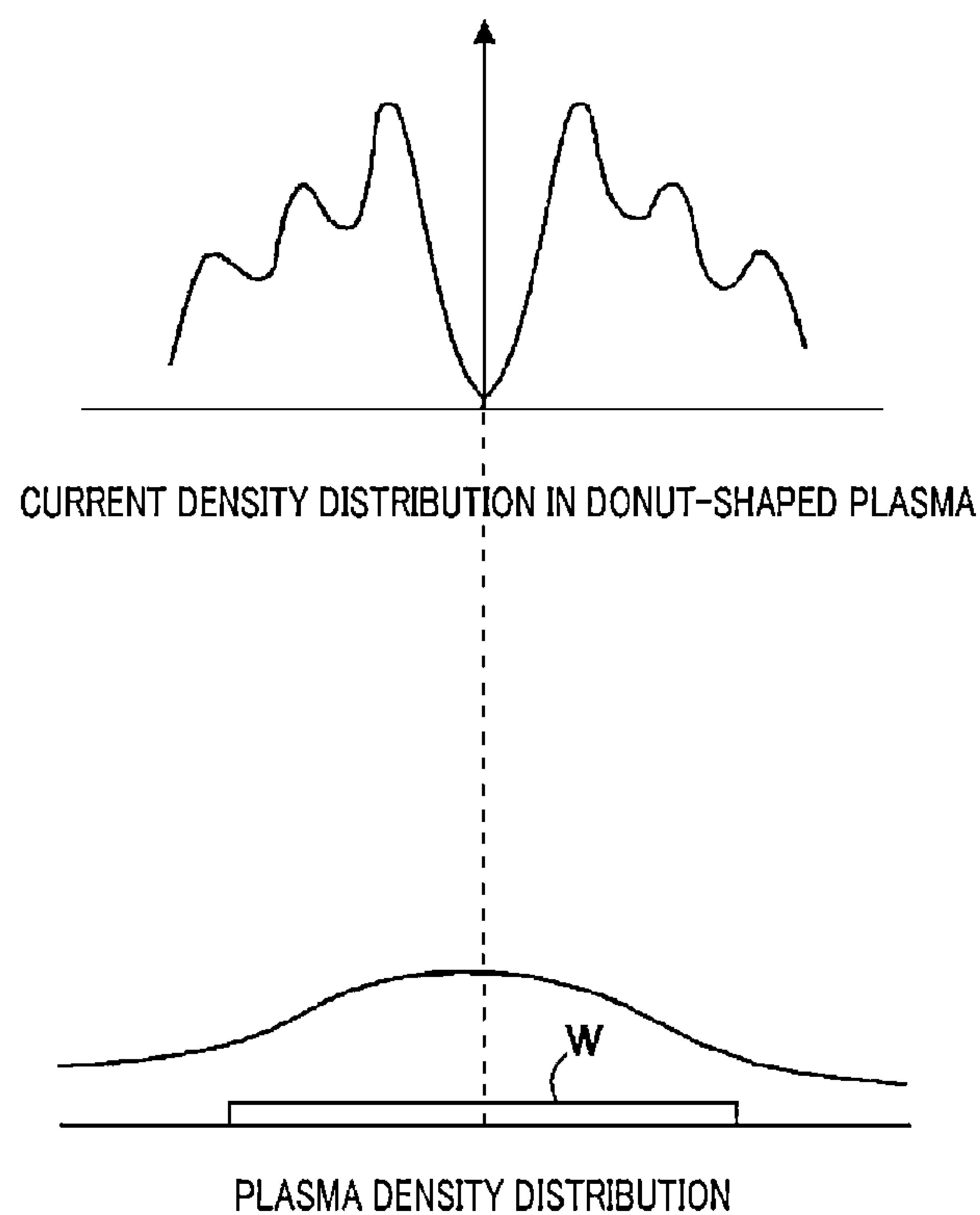


FIG. 5A

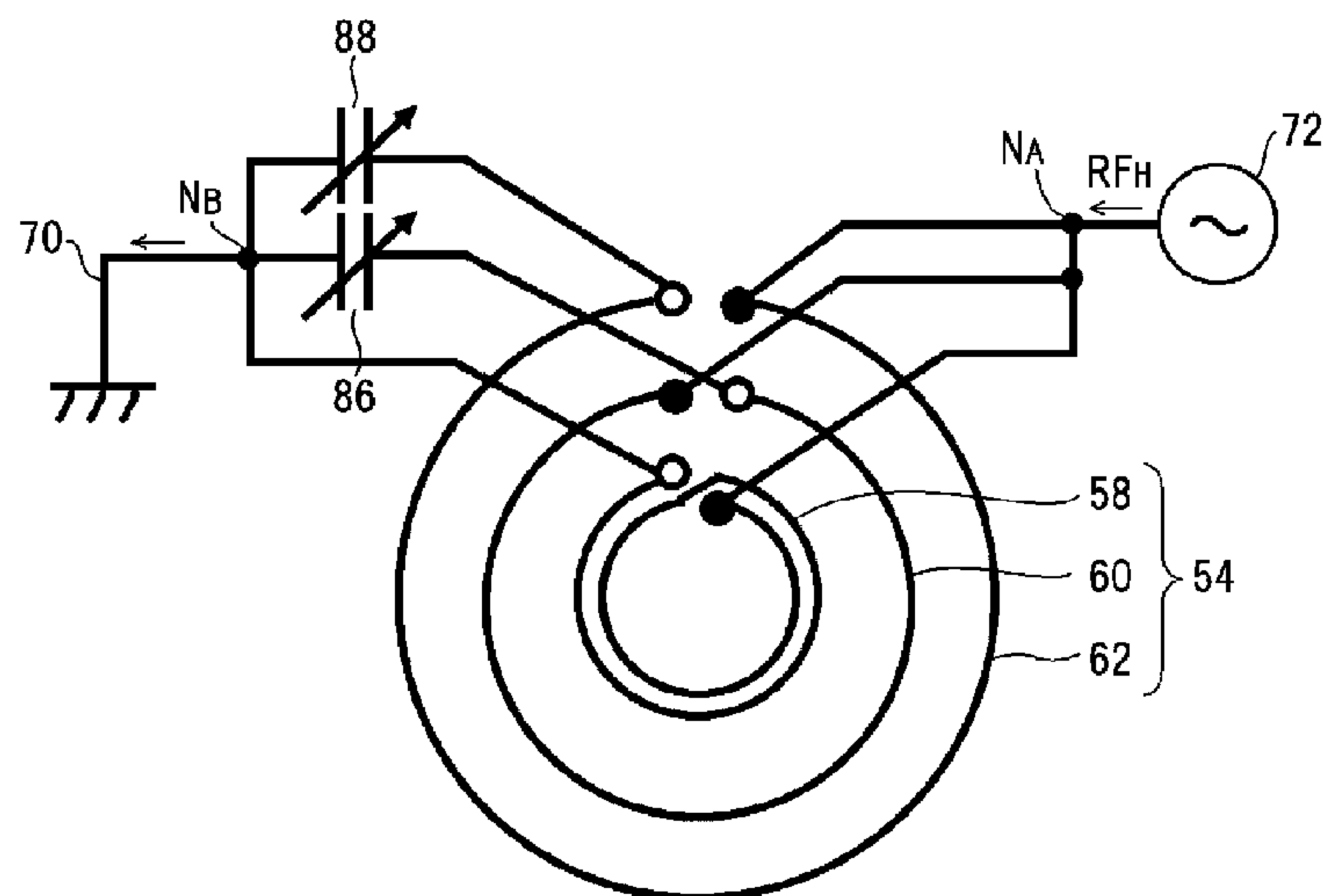


FIG. 5B

C (PF)	COIL CURRENT (A)	ELECTRON DENSITY DISTRIBUTION
13	φ300: 18.3, φ200: -0.4, φ100: 16.4	
40	φ300: 19.4, φ200: -5.0, φ100: 17.4	
64	φ300: 20.1, φ200: -11.2, φ100: 19.0	

FIG. 6A

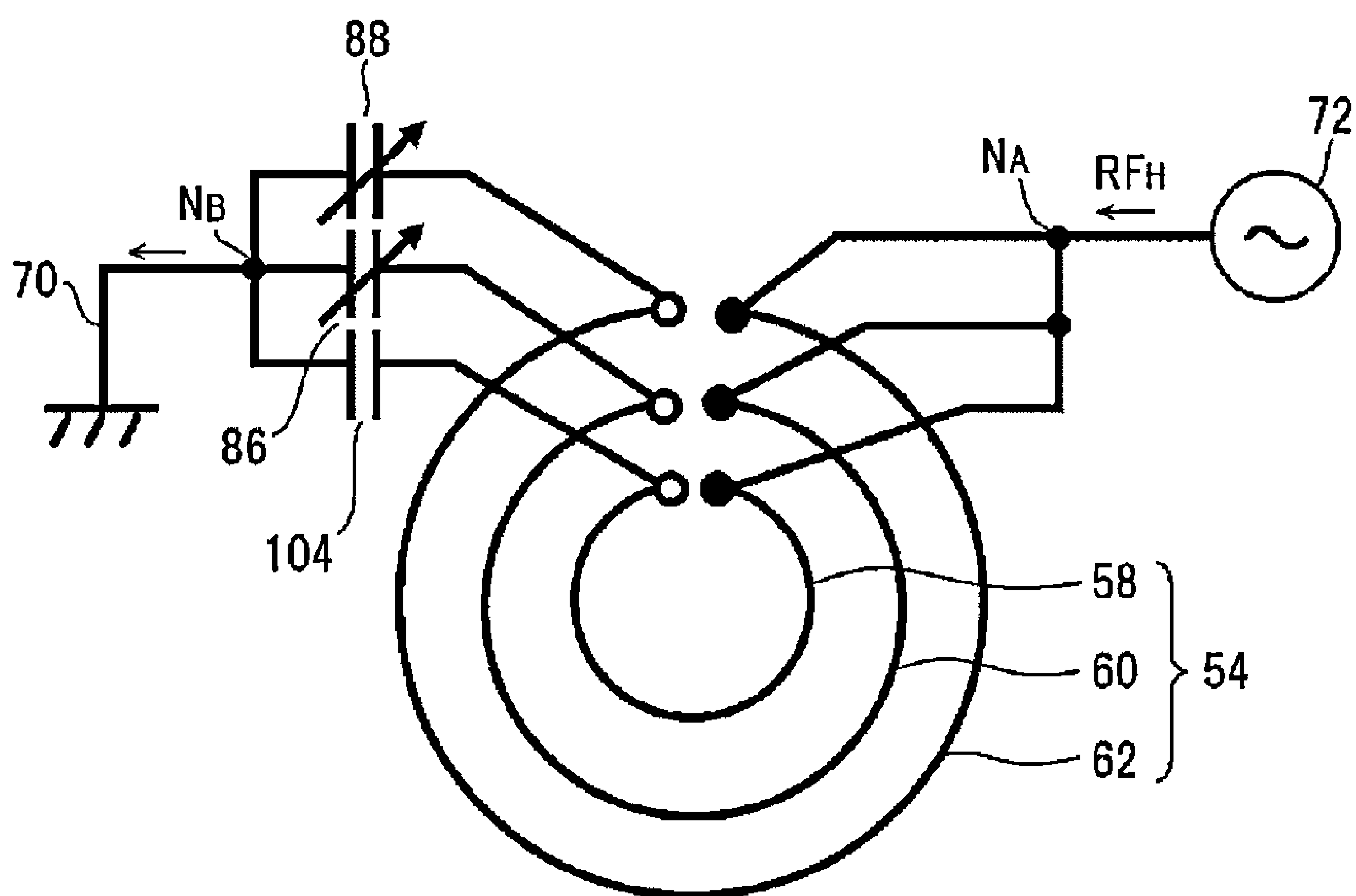


FIG. 6B

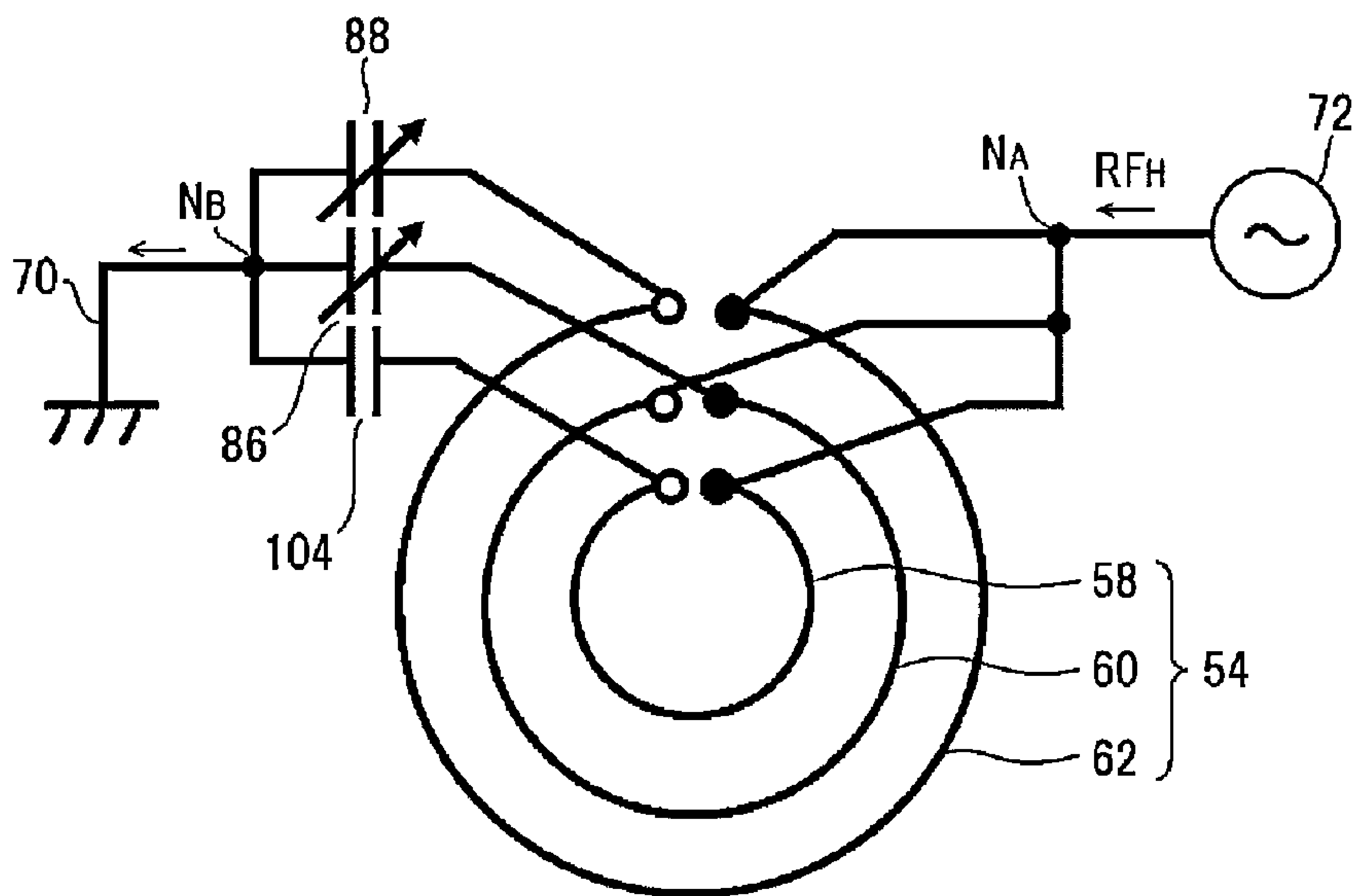


FIG. 7A

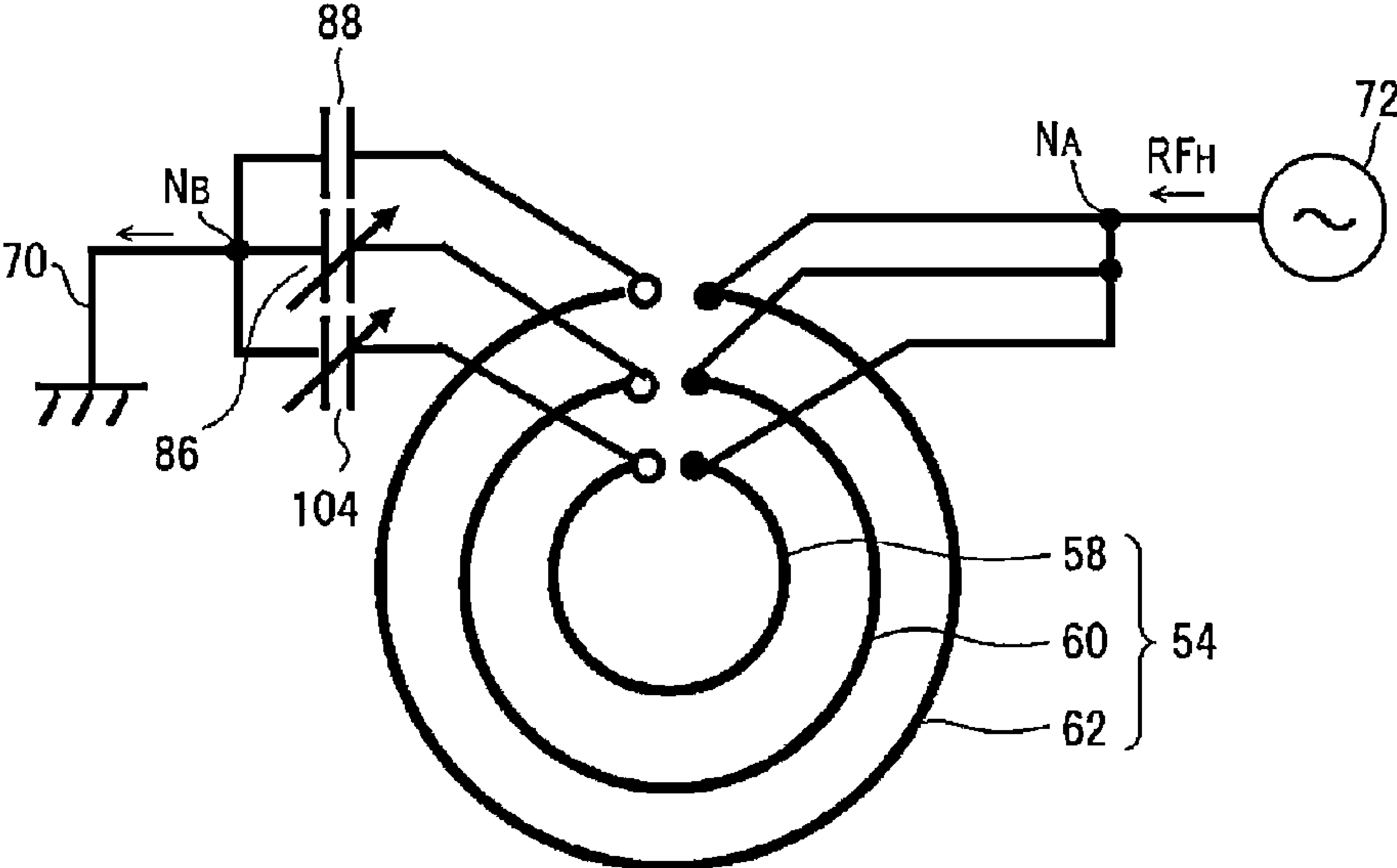


FIG. 7B

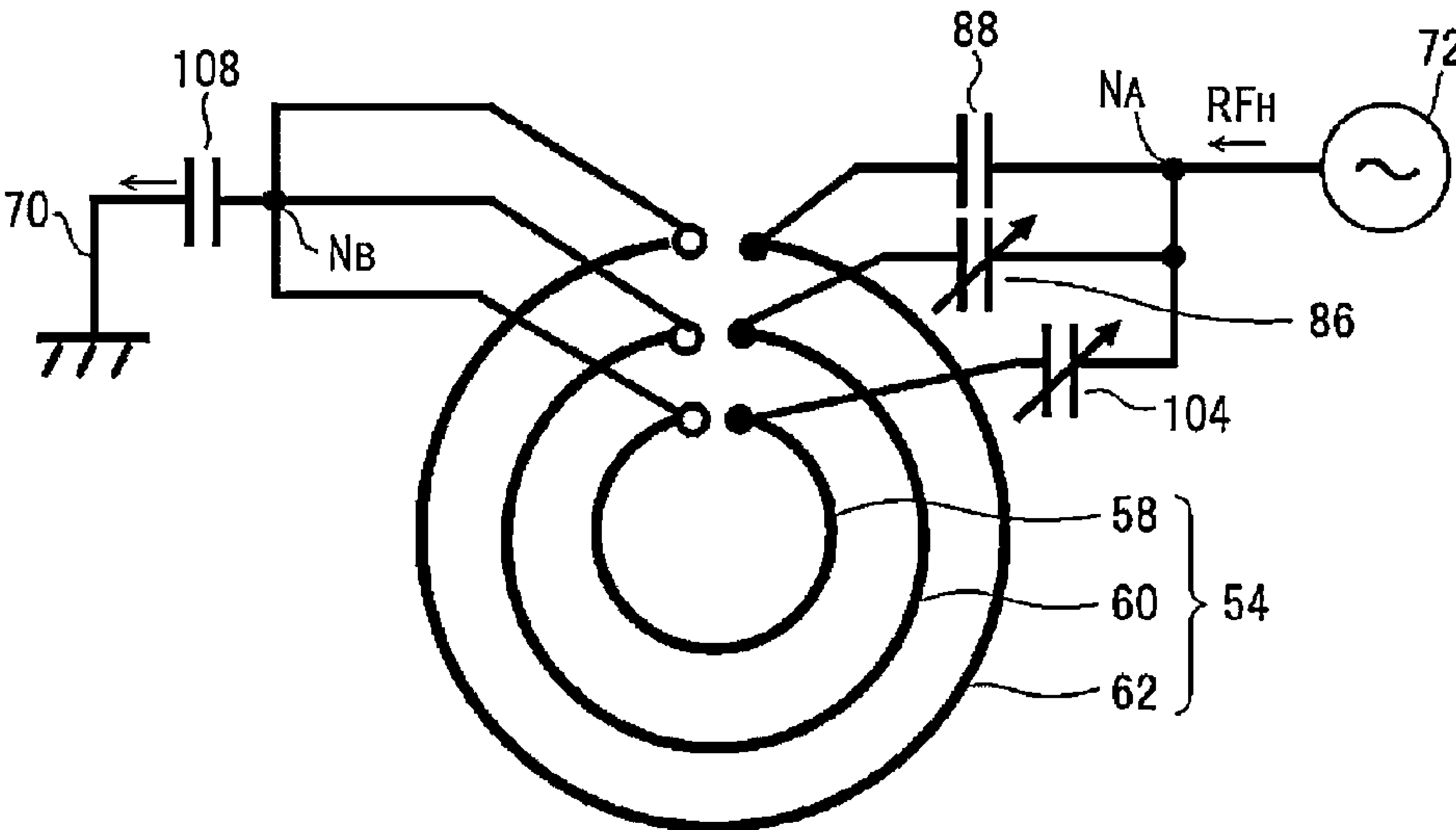


FIG. 8

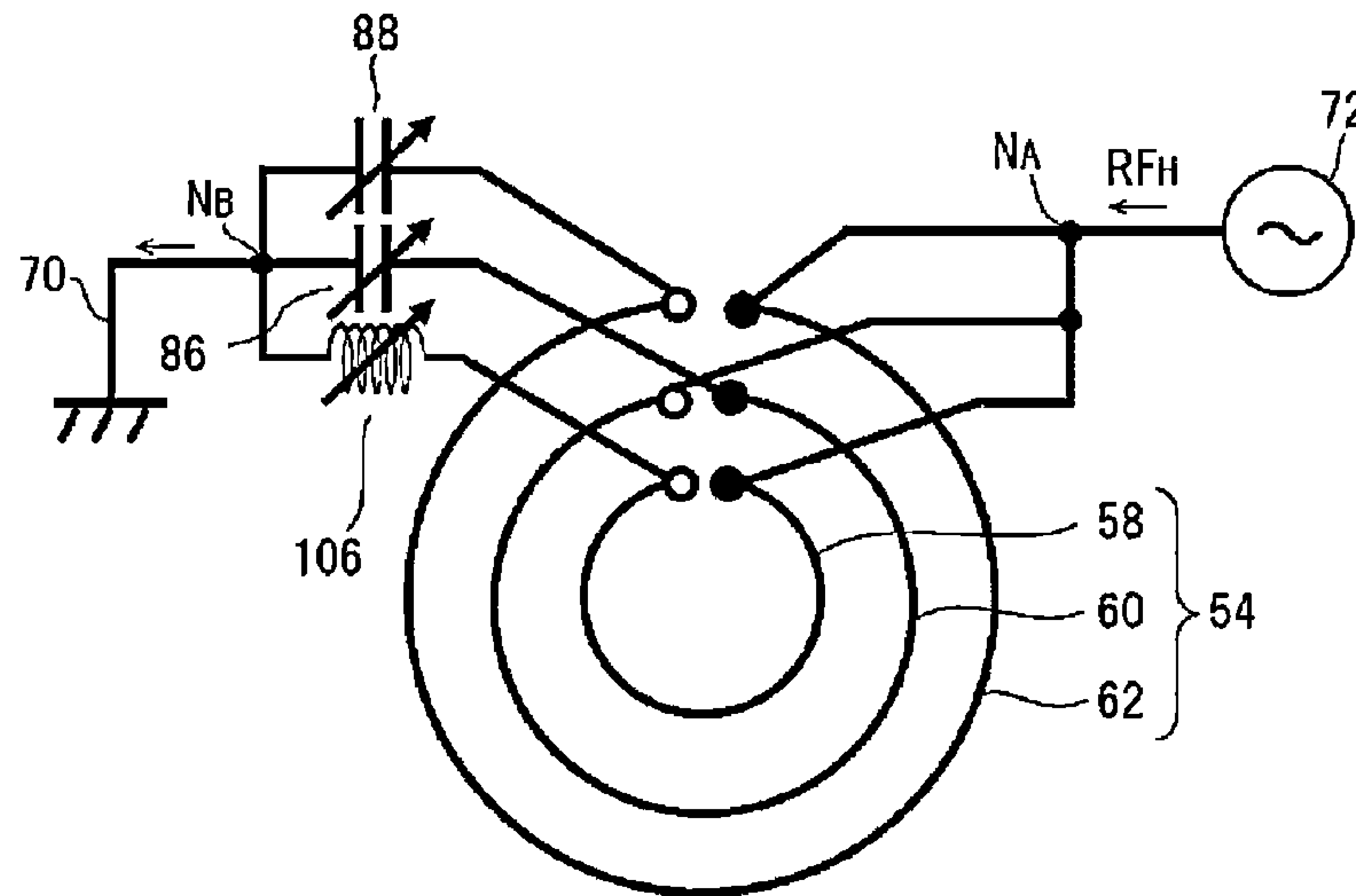


FIG. 9

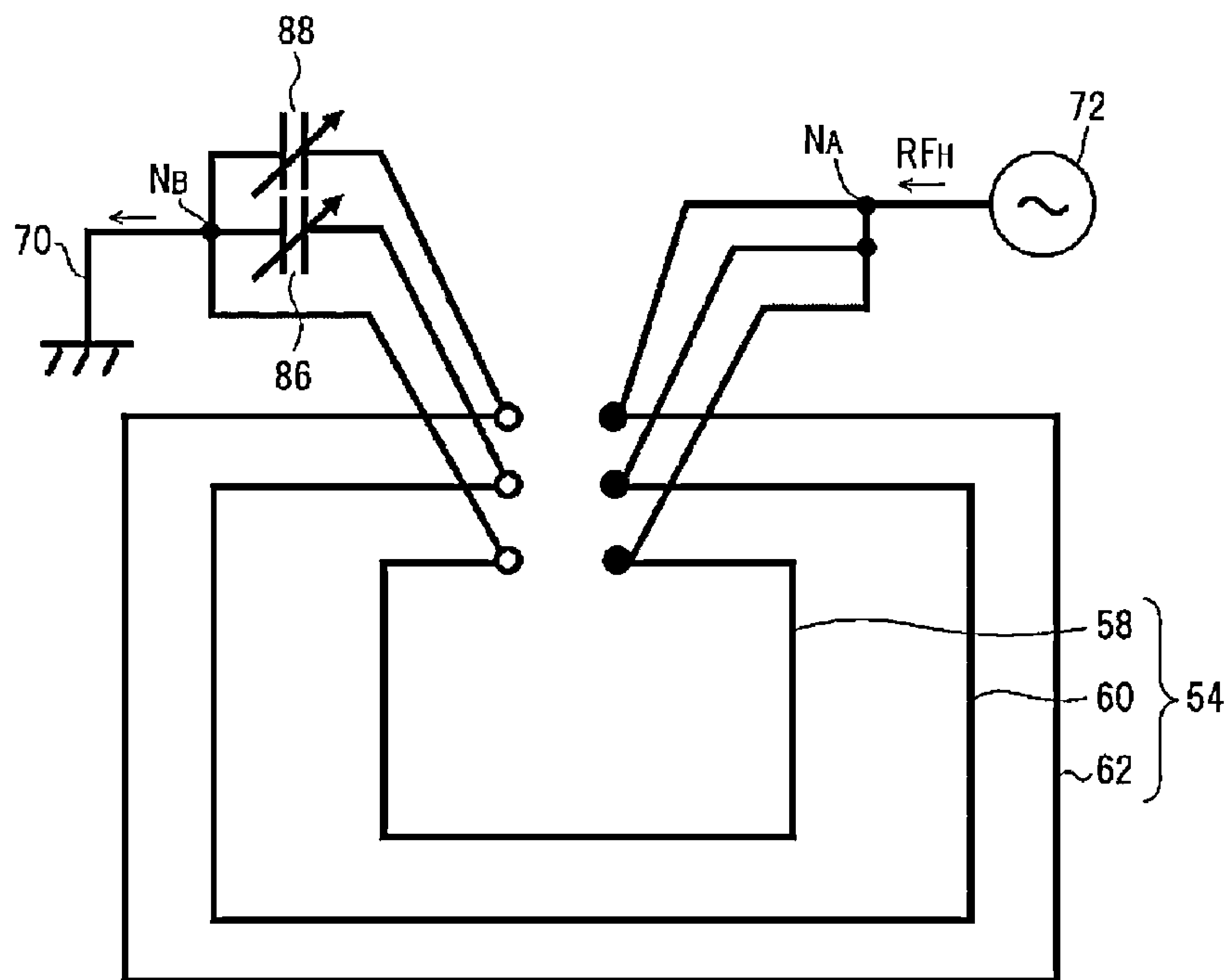


FIG. 10

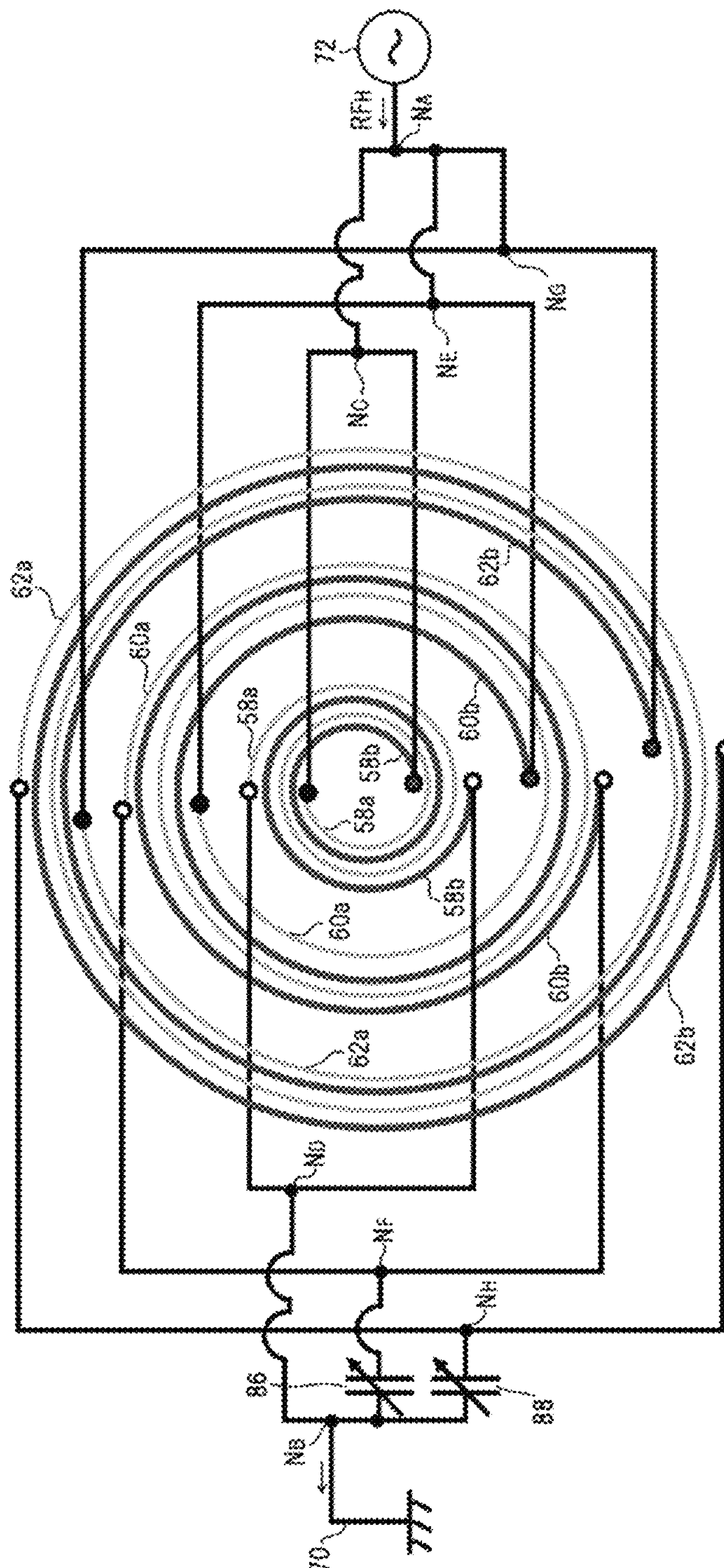


FIG. 11

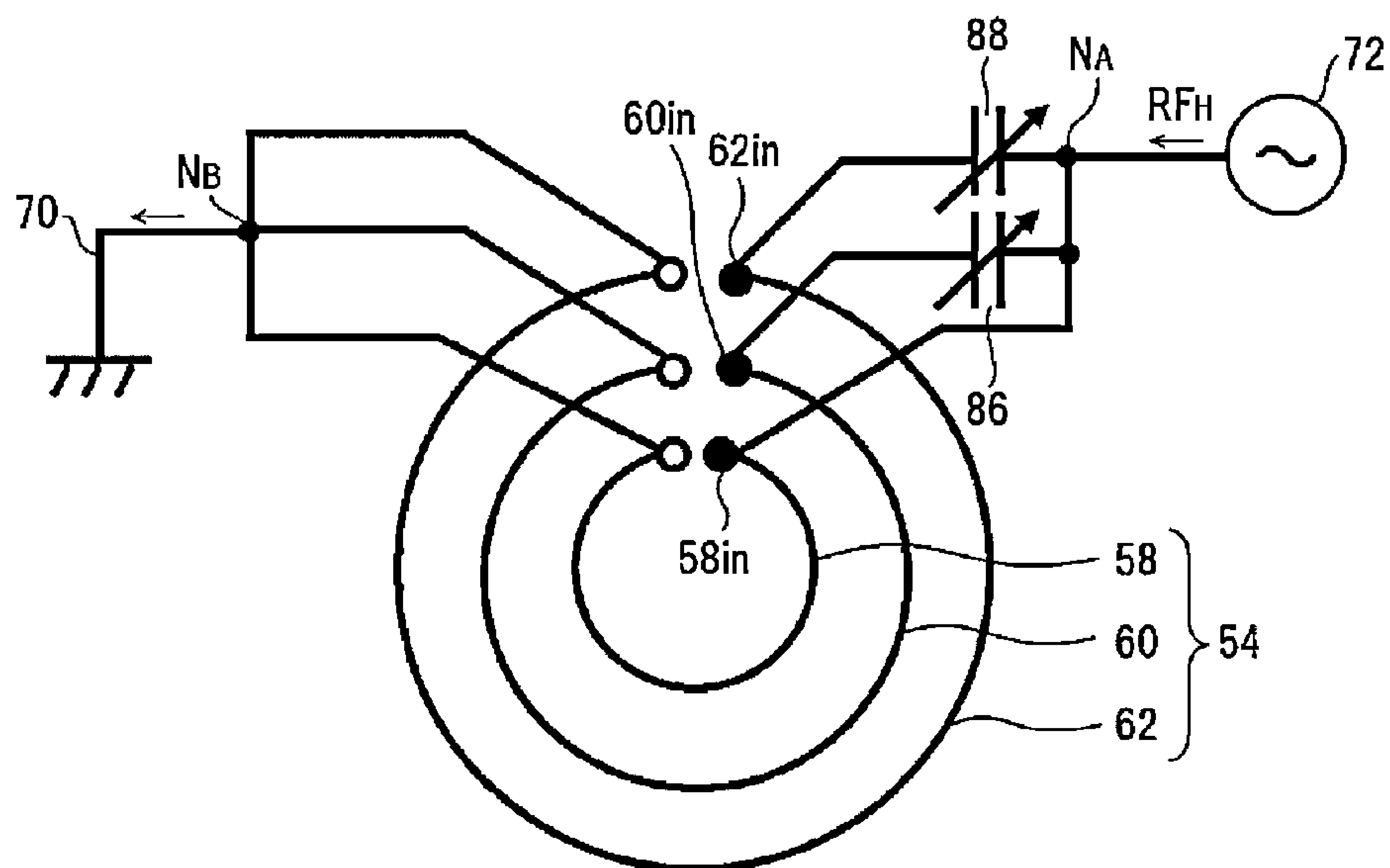
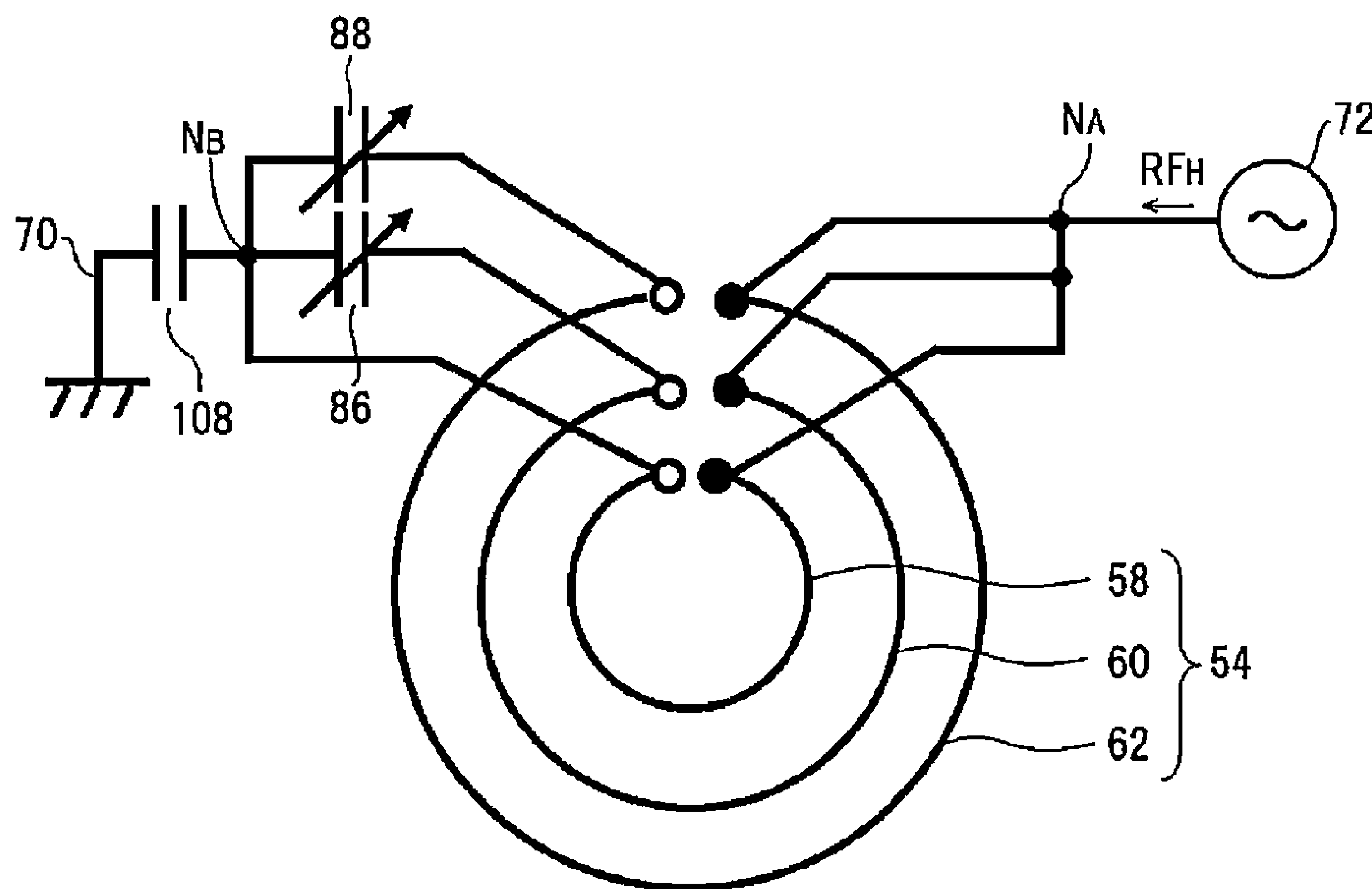


FIG. 12



PLASMA PROCESSING METHOD

CROSS-REFERENCE TO RELATED APPLICATION

This is a divisional application of U.S. patent application Ser. No. 13/434,802, filed on Mar. 29, 2012 which claims the benefit of Japanese Patent Application No. 2011-072582 filed on Mar. 29, 2011 and U.S. Provisional Application No. 61/472,671 filed on Apr. 7, 2011, the entire disclosures of which are incorporated herein by reference.

FIELD OF THE INVENTION

The present disclosure relates to a technique for performing a plasma process on a processing target substrate; and, more particularly, to an inductively coupled plasma processing apparatus and a plasma processing method.

BACKGROUND OF THE INVENTION

In a manufacturing process of a semiconductor device or a FPD (Flat Panel Display), plasma is used to perform a process, such as etching, deposition, oxidation or sputtering, so as to perform a good reaction of a processing gas at a relatively low temperature. Conventionally, plasma generated by a high frequency electric discharge in MHz frequency band has been used in this kind of plasma process. The plasma generated by the high frequency electric discharge is largely divided into capacitively coupled plasma and inductively coupled plasma according to a plasma generation method (in view of an apparatus).

Generally, in an inductively coupled plasma processing apparatus, at least a part (for example, a ceiling) of walls of a processing chamber may have a dielectric window, and a high frequency power is supplied to a coil-shaped RF antenna positioned at an outside of this dielectric window. The processing chamber serves as a depressurizable vacuum chamber, and a target substrate (for example, a semiconductor wafer and a glass substrate) is provided at a central region within the chamber. A processing gas is supplied into a processing space formed between the dielectric window and the substrate. A high frequency AC magnetic field having magnetic force lines is generated around the RF antenna by a high frequency current flowing in the RF antenna. The magnetic force lines of the high frequency AC magnetic field are transmitted to the processing space within the chamber via the dielectric window. As the RF magnetic field of the high frequency AC magnetic field changes with time, an inductive electric field is generated in an azimuth direction within the processing space. Then, electrons accelerated by this inductive electric field in the azimuth direction collide with molecules or atoms of the processing gas so as to be ionized. In this process, donut-shaped plasma may be generated.

Since a large processing space is formed within the chamber, the donut-shaped plasma can be diffused efficiently in all directions (particularly, in a radial direction) and a plasma density on the substrate becomes very uniform. However, only with a conventional RF antenna, the plasma density on a substrate is not sufficiently uniform for most plasma processes. In the plasma process, it is also one of the important issues to improve uniformity of a plasma density on a substrate since a uniformity/reproducibility and a production yield of a plasma process depend on the plasma uniformity.

In the inductively coupled plasma processing apparatus, a characteristic (profile) of plasma density distribution within the donut-shaped plasma formed in the vicinity of the dielectric window within the chamber is important. Especially, the profile of the plasma density distribution affects characteristics (especially, uniformity) of plasma density distribution on the substrate after the diffusion of the plasma.

In this regard, there have been proposed several methods for improving uniformity of plasma density distribution in a diametrical direction by dividing the RF antennal into a multiple number of circular ring-shaped coils each having different diameter. There are two types of RF antenna division methods: a first type of connecting the multiple number of circular ring-shaped coils in series (see, for example, Patent Document 1) and a second type of connecting the multiple number of circular ring-shaped coils in parallel (see, for example, Patent Document 2).

Patent Document 1: U.S. Pat. No. 5,800,619

Patent Document 1: U.S. Pat. No. 6,164,241

In accordance with the first type method among the aforementioned conventional RF antenna division methods, since an entire coil length of the RF antenna is large as a sum of all the coils, a voltage drop within the RF antenna may be fairly large and not negligible. Further, due to a wavelength effect, a standing wave of electric current having a node in the vicinity of a RF input terminal of the RF antenna may be easily formed. For these reasons, in accordance with this first type method, it may be difficult to achieve uniformity of plasma density distribution in a diametrical direction as well as in a circumferential direction. Thus, the first type method is essentially deemed to be inadequate for a plasma process for which plasma of a large diameter is necessary.

Meanwhile, in accordance with the second type method, the wavelength effect and the voltage drop within the RF antenna depend on a length of each of the coils segmented in parallel. Thus, the voltage drop within the antenna is relatively small. The second type method is advantageous in suppressing the wavelength effect. However, in the second type method, it is difficult to properly control current distribution within the RF antenna in a diametrical direction, and furthermore, the plasma density distribution right below the antenna.

Therefore, in the conventional plasma processing apparatus employing the second type method, variable capacitors for adjusting impedance are additionally added(connected) to respective coils within the RF antenna so as to adjust a ratio of RF currents flowing through the respective coils. However, since the variable capacitors are highly expensive, it is not desirable in costs to use the variable capacitors for all coils within the antenna. As the number of the variable capacitors increases, electrostatic capacitances (parameters) to be adjusted increase. Thus, adjustment works are complicated.

Meanwhile, the conventional methods do not effectively overcome an undesired profile, where the plasma density becomes relatively higher at a central portion of the diametrical direction. Especially, in a low pressure process, the plasma density may become easily higher at the central portion of the diametrical direction as a result of plasma diffusion. This problem is not easily resolved by the conventional methods. In a large-diameter plasma processing apparatus, a difference in a coil diameter between an inner coil and an outer coil is large. Thus, the plasma density strongly tends to become relatively higher at the central portion of the diametrical direction. The conventional methods could not have effectively achieved the uniformity of the plasma density distribution.

BRIEF SUMMARY OF THE INVENTION

In view of the above, the present illustrative embodiments provide an inductively coupled plasma processing apparatus and a plasma processing method, which are capable of effectively and easily controlling plasma density distribution within donut-shaped plasma in a diametrical direction. Especially, it is possible to effectively and variously control the plasma density distribution in the diametrical direction to be a proper profile when a pressure is low or plasma of a large diameter is necessary.

In accordance with one aspect of an illustrative embodiment, there is provided a plasma processing apparatus. The plasma processing apparatus includes a processing chamber having a dielectric window; a substrate holding unit for holding thereon a processing target substrate within the processing chamber; a processing gas supply unit configured to supply a processing gas into the processing chamber in order to perform a plasma process on the processing target substrate; an RF antenna provided outside the dielectric window in order to generate plasma of the processing gas within the processing chamber by inductive coupling; and a high frequency power supply unit configured to supply a high frequency power having a frequency for generating a high frequency electric discharge of the processing gas in the RF antenna. The RF antenna may include an inner coil, an intermediate coil, and an outer coil with gaps therebetween in a radial direction, respectively. Further, the inner coil, the intermediate coil and the outer coil may be electrically connected to one another in parallel between a first node and a second node provided in high frequency transmission lines of the high frequency power supply unit. Furthermore, a variable intermediate capacitor and a variable outer capacitor may be provided between the first node and the second node, and the variable intermediate capacitor may be electrically connected in series to the intermediate coil, and the variable outer capacitor may be electrically connected in series to the outer coil. Moreover, no reactance device may be connected to the inner coil between the first node and the second node.

In accordance with another aspect of the illustrative embodiment, there is provided a plasma processing apparatus. The plasma processing apparatus includes a processing chamber having a dielectric window; a substrate holding unit for holding thereon a processing target substrate within the processing chamber; a processing gas supply unit configured to supply a processing gas into the processing chamber in order to perform a plasma process on the processing target substrate; an RF antenna provided outside the dielectric window in order to generate plasma of the processing gas within the processing chamber by inductive coupling; and a high frequency power supply unit configured to supply a high frequency power having a frequency for generating a high frequency electric discharge of the processing gas in the RF antenna. The RF antenna may include an inner coil, an intermediate coil, and an outer coil with gaps therebetween in a radial direction, respectively. Further, the inner coil, the intermediate coil and the outer coil may be electrically connected to one another in parallel between a first node and a second node provided in high frequency transmission lines of the high frequency power supply unit. Furthermore, a fixed or semi-fixed inner capacitor, a variable intermediate capacitor, and a variable outer capacitor may be provided between the first node and the second node, and the fixed or semi-fixed inner capacitor may be electrically connected to the inner coil. Moreover, the variable intermediate capacitor may be electrically connected in series to the intermediate coil, and the variable outer capacitor may be electrically connected in series to the outer coil.

In accordance with still another aspect of the illustrative embodiment, there is provided a plasma processing apparatus. The plasma processing apparatus includes a processing chamber having a dielectric window; a substrate holding unit for holding thereon a processing target substrate within the processing chamber; a processing gas supply unit configured to supply a processing gas into the processing chamber in order to perform a plasma process on the processing target substrate; an RF antenna provided outside the dielectric window in order to generate plasma of the processing gas within the processing chamber by inductive coupling; and a high frequency power supply unit configured to supply a high frequency power having a frequency for generating a high frequency electric discharge of the processing gas in the RF antenna. The RF antenna may include an inner coil, an intermediate coil, and an outer coil with gaps therebetween in a radial direction, respectively. Further, the inner coil, the intermediate coil and the outer coil may be electrically connected to one another in parallel between a first node and a second node provided in high frequency transmission lines of the high frequency power supply unit. Furthermore, a fixed or semi-fixed inner inductor, a variable intermediate capacitor, and a variable outer capacitor may be provided between the first node and the second node, and the fixed or semi-fixed inner inductor may be electrically connected to the inner coil. Moreover, the variable intermediate capacitor may be electrically connected in series to the intermediate coil, and the variable outer capacitor is electrically connected in series to the outer coil.

In accordance with still another aspect of the illustrative embodiment, there is provided a plasma processing method for performing a plasma process on a processing target substrate by using a plasma processing apparatus. The plasma processing apparatus includes a processing chamber having a dielectric window; a substrate holding unit for holding thereon a processing target substrate within the processing chamber; a processing gas supply unit configured to supply a processing gas into the processing chamber in order to perform a plasma process on the processing target substrate; an RF antenna provided outside the dielectric window in order to generate plasma of the processing gas within the processing chamber by inductive coupling; and a high frequency power supply unit configured to supply a high frequency power having a frequency for generating a high frequency electric discharge of the processing gas in the RF antenna. The plasma processing method includes: segmenting the RF antenna into an inner coil, an intermediate coil, and an outer coil with gaps therebetween in a radial direction, respectively, the inner coil, the intermediate coil and the outer coil being electrically connected to one another in parallel between a first node and a second node provided in high frequency transmission lines of the high frequency power supply unit; providing a variable intermediate capacitor and a variable outer capacitor between the first node and the second node, the variable intermediate capacitor being electrically connected in series to the intermediate coil, the variable outer capacitor being electrically connected in series to the outer coil, no reactance device being connected to the inner coil; and controlling plasma density distribution on the substrate by selecting or variably adjusting electrostatic capacitances of the intermediate capacitor and the outer capacitor.

In the plasma processing apparatus or the plasma processing method, when a high frequency power is supplied from the high frequency power supply unit to the RF antenna, an RF magnetic field is generated around each of the inner coil, the intermediate coil, and the outer coil of the RF antenna by high frequency currents flowing in the respective coils. Further, an inductive electric field configured to generate high frequency electric discharge of the processing gas, i.e., donut-shaped plasma in the processing chamber is formed. The generated donut-shaped plasma is diffused in all directions within the processing chamber, so that the plasma density on the substrate is uniformized.

When directions of the coil currents flowing in the inner coil, the intermediate coil, and the outer coil, respectively, are identical to the circumferential direction, the plasma density within the donut-shaped plasma has a maximum value at portions corresponding to the respective coils. In this case, by varying or adjusting electrostatic capacitances of the intermediate capacitor and the outer capacitor, an intermediate coil current flowing in the intermediate coil and an outer coil current flowing in the outer coil are varied with respect to an inner coil current flowing in the inner coil. In this manner, it is possible to control the plasma density distribution within the donut-shaped plasma, and furthermore, the plasma density distribution on the substrate.

Further, it is possible to flow the intermediate coil current or the outer coil current in a direction opposite to the other coil current by adjusting the electrostatic capacitance of the intermediate capacitor or the electrostatic capacitance of the outer capacitor. In this case, it is possible to locally lower the plasma density at the portion in the donut-shaped plasma, corresponding to the intermediate coil or the outer coil. Furthermore, a freedom degree of the plasma density distribution control on the substrate can be expanded.

In accordance with still another aspect of the illustrative embodiment, there is provided a plasma processing apparatus. The plasma processing apparatus includes a processing chamber having a dielectric window; a substrate holding unit for holding thereon a processing target substrate within the processing chamber; a processing gas supply unit configured to supply a processing gas into the processing chamber in order to perform a plasma process on the processing target substrate; an RF antenna provided outside the dielectric window in order to generate plasma of the processing gas within the processing chamber by inductive coupling; and a high frequency power supply unit configured to supply a high frequency power having a frequency for generating a high frequency electric discharge of the processing gas in the RF antenna. The RF antenna may include an inner coil, an intermediate coil, and an outer coil with gaps therebetween in a radial direction, respectively. Further, the inner coil, the intermediate coil and the outer coil may be electrically connected to one another in parallel between a first node and a second node provided in high frequency transmission lines of the high frequency power supply unit. Furthermore, a variable inner capacitor, a variable intermediate capacitor, and a fixed or semi-fixed outer capacitor may be provided between the first node and the second node, and the variable inner capacitor may be electrically connected to the inner coil. Moreover, the variable intermediate capacitor may be electrically connected in series to the intermediate coil, and the fixed or semi-fixed outer capacitor may be electrically connected in series to the outer coil.

In the plasma processing apparatus, when a high frequency power is supplied from the high frequency power supply unit to the RF antenna, an RF magnetic field is generated around each of the inner coil, the intermediate coil, and the outer coil of the RF antenna by high frequency currents flowing in the respective coils. Further, an inductive electric field configured to generate high frequency electric discharge of the processing gas, i.e., donut-shaped plasma in the processing chamber is formed. The generated donut-shaped plasma is diffused in all directions within the processing chamber, so that the plasma density on the substrate is uniformized.

When directions of the coil currents flowing in the inner coil, the intermediate coil, and the outer coil, respectively, are identical to the circumferential direction, the plasma density within the donut-shaped plasma has a maximum value at a portion corresponding to each of the coils. In this case, by varying or adjusting electrostatic capacitances of the intermediate capacitor and the inner capacitor, an intermediate coil current flowing in the intermediate coil and an inner coil current flowing in the inner coil, respectively, are varied with respect to an outer coil current flowing in the outer coil. In this manner, it is possible to control the plasma density distribution within the donut-shaped plasma, and furthermore, the plasma density distribution on the substrate.

Further, it is possible to flow the intermediate coil current in a direction opposite to the other coil currents by adjusting the electrostatic capacitance of the intermediate capacitor. In this case, it is possible to locally lower the plasma density at a portion in the donut-shaped plasma, corresponding to the intermediate coil or the outer coil. Furthermore, a freedom degree of the plasma density distribution control on the substrate can be expanded.

In accordance with the plasma processing apparatus or the plasma processing method of the illustrative embodiment, it is possible to effectively and easily control the plasma density distribution within the donut-shaped plasma, with the above-described configuration and operation. Especially, it is possible to effectively and variously control the plasma density distribution in the diametrical direction to have a proper profile when a pressure is low or plasma of a large diameter is necessary.

BRIEF DESCRIPTION OF THE DRAWINGS

Non-limiting and non-exhaustive embodiments will be described in conjunction with the accompanying drawings. Understanding that these drawings depict only several embodiments in accordance with the disclosure and are, therefore, not to be intended to limit its scope, the disclosure will be described with specificity and detail through use of the accompanying drawings, in which:

FIG. **1** is a longitudinal cross sectional view showing a configuration of an inductively coupled plasma processing apparatus in accordance with an example of an illustrative embodiment;

FIG. **2** is a perspective view showing a basic configuration of a layout and an electric connection of a variable capacitor provided within RF antenna in accordance with the illustrative embodiment;

FIG. **3** is a diagram illustrating operation of an experimental example of FIG. **2**;

FIG. **4** is a diagram showing electrical connection and an operation of the electrical connection when capacitors are omitted in the RF antenna of FIG. **2**;

FIG. **5**A is a diagram showing a basic configuration of a layout and an electric connection of a variable capacitor added in RF antenna for an experiment in accordance with the illustrative embodiment;

FIG. **5**B is a diagram showing coil current distribution and electron density distribution measured by varying electrostatic capacitance of an intermediate capacitor in the above-described experiment;

FIG. **6**A is a diagram showing a basic configuration of a layout and an electric connection of a variable capacitor added in RF antenna in a modified example of the illustrative embodiment;

FIG. **6**B is an explanatory view illustrating operation of the experimental example of FIG. **6**A;

FIG. **7**A is a diagram showing a basic configuration of a layout and an electric connection of a variable capacitor added in RF antenna in another experimental example;

FIG. **7**B is a diagram showing a basic configuration of a layout and an electric connection of a variable capacitor added in RF antenna in another experimental example;

FIG. **8** is a diagram showing a basic configuration of a layout and an electric connection of a variable capacitor added in RF antenna in another experimental example;

FIG. **9** is a diagram showing a basic configuration of a layout and an electric connection of a variable capacitor added in RF antenna in another experimental example;

FIG. **10** is a diagram showing a basic configuration of a layout and an electric connection of a variable capacitor added in RF antenna in another experimental example;

FIG. **11** is a diagram showing a basic configuration of a layout and an electric connection of a variable capacitor added in RF antenna in another experimental example; and

FIG. **12** is a diagram showing a basic configuration of a layout and an electric connection of a variable capacitor added in RF antenna in another experimental example.

DETAILED DESCRIPTION OF THE INVENTION

Hereinafter, illustrative embodiments will be described with reference to the accompanying drawings.

[Entire Configuration and Operation of Apparatus]

FIG. **1** illustrates a configuration of an inductively coupled plasma processing apparatus in accordance with an illustrative embodiment.

The plasma processing apparatus is configured as an inductively coupled plasma etching apparatus using a planar coil RF antenna. By way of example, the plasma etching apparatus may include a cylindrical vacuum chamber (processing chamber) **10** made of metal such as aluminum or stainless steel. The chamber **10** may be frame grounded.

Above all, there will be explained a configuration of each component which is not related to plasma generation in this inductively coupled plasma etching apparatus.

At a lower central region within the chamber **10**, a circular plate-shaped susceptor **12** may be provided horizontally. The susceptor **12** may mount thereon a target substrate such as a semiconductor wafer W and may serve as a high frequency electrode as well as a substrate holder. This susceptor **12** may be made of, for example, aluminum and may be supported by a cylindrical insulating support **14** which may be extended uprightly from a bottom of the chamber **10**.

Between a cylindrical conductive support **16** which is extended uprightly from a bottom of the chamber **10** along the periphery of the cylindrical insulating support **14** and an inner wall of the chamber **10**, an annular exhaust line **18** may be provided. Further, an annular baffle plate **20** may be provided at an upper portion or an input of the exhaust line **18**. Further, an exhaust port **22** may be provided at a bottom portion. In order for a gas flow within the chamber **10** to be uniformized with respect to an axis of the semiconductor wafer W on the susceptor **12**, multiple exhaust ports **22** equi-spaced from each other along a circumference may be provided. Each exhaust port **22** may be connected to an exhaust unit **26** via an exhaust pipe **24**. The exhaust unit **26** may include a vacuum pump such as a turbo molecular pump or the like. Thus, it may be possible to depressurize a plasma generation space within the chamber **10** to a required vacuum level. At an outside of a sidewall of the chamber **10**, a gate valve **28** configured to open and close a loading/unloading port **27** of the semiconductor wafer W may be provided.

The susceptor **12** may be electrically connected to a high frequency power supply **30** for RF bias via a matching unit **32** and a power supply rod **34**. This high frequency power supply **30** may be configured to output a variable high frequency power RF_L having an appropriate frequency (typically, about 13.56 MHz or less) to control energies of ions attracted into the semiconductor wafer W. The matching unit **32** may accommodate a variable reactance matching circuit for performing matching between an impedance of the high frequency power supply **30** and an impedance of a load (mainly, susceptor, plasma and chamber). The matching circuit may include a blocking capacitor configured to generate a self-bias.

An electrostatic chuck **36** for holding the semiconductor wafer W by an electrostatic attraction force may be provided on an upper surface of the susceptor **12**. Further, a focus ring **38** may be provided around the electrostatic chuck **36** to annularly surround the periphery of the semiconductor wafer W. The electrostatic chuck **36** may be formed by placing an electrode **36***a* made of a conductive film between a pair of insulating films **36***b* and **36***c*. A high voltage DC power supply **40** may be electrically connected to the electrode **36***a* via a switch **42** and a coated line **43**. By applying a high DC voltage from the high voltage DC power supply **40**, the semiconductor wafer W can be attracted to and held on the electrostatic chuck **36** by the electrostatic force.

A coolant cavity or a coolant path **44** of, e.g., a circular ring-shape, may be formed within the susceptor **12**. A coolant, such as cooling water cw, having a certain temperature may be supplied into and circulated through the coolant path **44** from a chiller unit (not illustrated) via lines **46** and **48**. By adjusting the temperature of the cooling water cw, it may be possible to control a process temperature of the semiconductor wafer W held on the electrostatic chuck **36**. Further, a heat transfer gas, such as a He gas, may be supplied from a heat transfer gas supply unit (not illustrated) into a space between an upper surface of the electrostatic chuck **36** and a rear surface of the semiconductor wafer W through a gas supply line **50**. Furthermore, an elevating mechanism (not shown) including lift pins configured to move up and down vertically through the susceptor **12** may be provided to load and unload the semiconductor wafer W.

Hereinafter, there will be explained a configuration of each component which is related to plasma generation in this inductively coupled plasma etching apparatus.

A ceiling or a ceiling plate of the chamber **10** may be separated relatively far from the susceptor **12**. A circular dielectric window **52** formed of, for example, a quartz plate may be airtightly provided as the ceiling plate. Above the dielectric window **52**, an antenna chamber **56** may be provided as a part of the chamber **10**. The antenna chamber **56** may accommodate therein a RF antenna **54** and shield this RF antenna **54** from the outside. Here, the RF antenna **54** may generate inductively coupled plasma within the chamber **10**.

The RF antenna **54** is provided in parallel to the dielectric window **52**. Desirably, the RF antenna **54** may be placed on the top surface of the dielectric window **52** and include an inner coil **58**, an intermediate coil **60**, and an outer coil **62** with a certain gap therebetween in a radial direction. The coils **58**, **60**, **62** are coaxially (preferably, concentrically) arranged. Further, the coils **58**, **60**, **62** are also arranged concentrically with each other as well as with the chamber **10** or the susceptor **12**.

In the illustrative embodiment, the term "coaxial" means that central axes of multiple objects having axisymmetric shape are aligned with each other. As for multiple coils, respective coils surfaces may be offset with each other in an axial direction or may be aligned on the same plane (positioned concentrically).

Further, the inner coil **58**, the intermediate coil **60** and the outer coil **62** are electrically connected in parallel between a high frequency power supply line **68** from a high frequency power supply unit **66** for plasma generation and a return line **70** toward a ground potential member (i.e., between two nodes N_A and N_B). Here, the return line **70** as an earth line is grounded and is connected with a ground potential member (for example, the chamber **10** or other member) that is electrically maintained at a ground potential.

A variable capacitor **86** is provided between the node N_B on the earth line **70** and the intermediate coil **60**. Further, a variable capacitor **88** is provided between the node N_B on the earth line **70** and the outer coil **62**. Capacitances of these variable capacitors **86** and **88** may be independently adjusted to a desired value within a certain range by a capacitance varying unit **90** under the control of a main controller **84**. Hereinafter, a capacitor connected in series to the inner coil **58** will be referred to as an "inner capacitor"; a capacitor connected in series to the intermediate coil **60** will be referred to as an "intermediate coil"; and a capacitor connected in series to the outer coil **62** will be referred to as an "outer capacitor." All these capacitors are provided between the node N_A and N_B.

The high frequency power supply unit **66** may include a high frequency power supply **72** and a matching unit **74**. The high frequency power supply **72** is capable of outputting a variable high frequency power RF_H having a frequency (typically, equal to or higher than about 13.56 MHz) for generating plasma by an inductively coupled high frequency electric discharge. The matching unit **74** has a reactance-variable matching circuit for performing matching between an impedance of the high frequency power supply **72** and an impedance of load (mainly, RF antenna or plasma).

A processing gas supply unit for supplying a processing gas into the chamber **10** may include an annular manifold or buffer unit **76**; multiple sidewall gas discharge holes **78**; and a gas supply line **82**. The buffer unit **76** may be provided at an inside (or outside) of the sidewall of the chamber **10** to be located at a position slightly lower than the dielectric window **52**. The sidewall gas discharge holes **78** may be formed along a circumference at a regular interval and opened to the plasma generation space from the buffer unit **76**. The gas supply line **82** may be extended from a processing gas supply source **80** to the buffer unit **76**. The processing gas supply source **80** may include a flow rate controller and an opening/closing valve (not shown).

The main controller **84** may include, for example, a micro computer and may control an operation of each component within this plasma etching apparatus, for example, the exhaust unit **26**, the high frequency power supplies **30** and **72**, the matching units **32** and **74**, the switch **42** for the electrostatic chuck, the variable capacitors **86** and **88**, the processing gas supply source **80**, the chiller unit (not shown), and the heat transfer gas supply unit (not shown) as well as a whole operation (sequence) of the apparatus.

In order to perform an etching process in this inductively coupled plasma etching apparatus, when the gate valve **28** becomes open, the semiconductor wafer W as a process target may be loaded into the chamber **10** and mounted on the electrostatic chuck **36**. Then, after closing the gate valve **28**, an etching gas (generally, an mixture gas) may be introduced into the chamber **10** from the processing gas supply source **80** via the gas supply line **82**, the buffer unit **76**, and the sidewall gas discharge holes **78** at a certain flow rate and a flow rate ratio. Subsequently, an internal pressure of the chamber **10** may be controlled to be a certain level by the exhaust unit **26**. Further, the high frequency power supply **72** of the high frequency power supply unit **66** is turned on, and the high frequency power RF_H for plasma generation is outputted at a certain RF power level. A current of the high frequency power RF_H is supplied to the inner coil **58**, the intermediate coil **60** and the outer coil **62** of the RF antenna **54** through the matching unit **74**, the RF power supply line **68** and the return line **70**. Meanwhile, the high frequency power supply **30** may be turned on to output the high frequency power RF_L for ion attraction control at a certain RF power level. This high frequency power RF_L may be applied to the susceptor **12** via the matching unit **32** and the power supply rod **34**. Further, a heat transfer gas (a He gas) may be supplied to a contact interface between the electrostatic chuck **36** and the semiconductor wafer W from the heat transfer gas supply unit. Furthermore, the switch **42** is turned on, and then, the heat transfer gas may be confined in the contact interface by the electrostatic force of the electrostatic chuck **36**.

Within the chamber **10**, an etching gas discharged from sidewall gas discharge holes **78** is diffused into a processing space below the dielectric window **52**. By the current of the high frequency power RF_H flowing in the coils **58**, **60** and **62**, magnetic force lines (magnetic flux) generated around these coils are transmitted to the processing space (plasma generation space) within the chamber **10** via the dielectric window **52**. An induced electric field may be generated in an azimuth direction within the processing space. Then, electrons accelerated by this induced electric field in the azimuth direction may collide with molecules or atoms of the etching gas so as to be ionized. In the process, donut-shaped plasma may be generated.

Radicals or ions in the donut-shaped plasma may be diffused in all directions within the large processing space. To be specific, while the radicals are isotropically introduced and the ions are attracted by a DC bias, the radicals and the ions may be supplied on an upper surface (target surface) of the semiconductor wafer W. Accordingly, plasma active species may perform chemical and physical reactions on the target surface of the semiconductor wafer W so as to etch a target film into a required pattern.

Herein, "donut-shaped plasma" is not limited to only ring-shaped plasma which is generated only at the radial outside in the chamber **10** without being generated at the radial inside (at a central area) therein. Further, "donut-shaped plasma" may include a state where a volume or a density of the plasma generated at the radial outside is greater than that at the radial inside. Further, depending on a kind of a gas used for the processing gas, an internal pressure of the chamber **10**, or the like, the plasma may have other shapes instead of "a donut shape".

In the inductively coupled plasma etching apparatus, the RF antenna **54** is segmented into the inner coil **58**, the intermediate coil **60**, and the outer coil **62**, which have different coil diameters. As a result, a wavelength effect or an electric potential difference (voltage drop) in the RF antenna **54** is effectively suppressed or reduced. Further, except for the inner coil **58**, the variable capacitors **86**, **88** are connected in series to the intermediate coil **60** and the outer coil **62**, respectively. Therefore, plasma density distribution on the semiconductor wafer W can be simply and effectively controlled.

[Basic Configuration and Operation of the RF Antenna]

FIGS. **2** and **3** illustrate a basic configuration of a layout and an electric connection (circuit) of the RF antenna **54** in accordance with the illustrative embodiment.

As illustrated in FIG. **2**, the inner coil **58** includes a single circular-ring shaped coil with a gap or a space G_i therein, and the inner coil **58** has a constant radius. Further, the inner coil **58** is positioned near a central portion of the processing chamber **10** in the diametrical direction. One end of the inner coil **58**, i.e., an RF input terminal **58***in* is connected to the RF power supply line **68** of the high frequency power supply unit **66** via the first node N_A and the connection conductor **92** extending upwardly. The other end of the inner coil **58**, i.e., an RF output terminal **58***out* is connected to the earth line **70** via the second node N_B and the connection conductor **94** extending upwardly.

The intermediate coil **60** includes a single circular-ring shaped coil with a gap or a space G_m therein, and the intermediate coil **60** has a constant radius. Further, the intermediate coil **60** is positioned at a portion of more outer than the inner coil **58** in the diametrical direction in a middle portion of the processing chamber **10**. One end of the intermediate coil **60**, i.e., an RF input terminal **60***in* is adjacent to the RF input terminal **58***in* of the inner coil **58** in the diametrical direction. Further, the RF input terminal **60***in* is connected to the RF power supply line **68** of the high frequency power supply unit **66** via the first node N_A and the connection conductor **96** extending upwardly. The other end of the intermediate coil **60**, i.e., an RF output terminal **60***out* is adjacent to the RF output terminal **58***out* of the inner coil **58** in the diametrical direction. Further, the RF output terminal **60***out* is connected to the earth line **70** via the second node N_B and the connection conductor **98** extending upwardly.

The outer coil **62** includes a single circular-ring shaped coil with a gap or a space G_o therein, and the outer coil **62** has a constant radius. The outer coil **62** is positioned at a portion of more outer than the intermediate coil **60** in the diametrical direction near the side wall of the processing chamber **10**. One end of the outer coil **62**, i.e., an RF input terminal **62***in* is adjacent to the RF input terminal **60***in* of the intermediate coil **60** in the diametrical direction. The RF input terminal **62***in* is connected to the RF power supply line **68** of the high frequency power supply unit **66** via the first node N_A and the connection conductor **100** extending upwardly. The other end of the outer coil **62**, i.e., an RF output terminal **62***out* is adjacent to the RF output terminal **60***out* of the intermediate coil **60** in the diametrical direction. The RF output terminal **62***out* is connected to the earth line **70** via the second node N_B and the connection conductor **102** extending upwardly.

As illustrated in FIG. **2**, the connection conductors **92** to **102** upwardly extending from the RF antenna **54** serve as branch lines or connecting lines in horizontal directions while spaced apart from the dielectric window **52** at a sufficiently large distance (i.e., at considerably high positions). Accordingly, electromagnetic influence upon the coils **58**, **60** and **62** can be reduced.

In the above-described coil arrangement and segment connection configuration within the RF antenna **54**, when connecting from the high frequency power supply **72** to the ground potential member via the RF power supply line **68**, the RF antenna **54**, and the earth line **70**, more directly, when connecting from the first node N_A to the second node N_B via high frequency branch transmission lines of the coils **58**, **60**, **62** within the RF antenna **54**, the directions when passing through the inner coil **58**, the intermediate coil **60**, and the outer coil **62** are all counterclockwise of FIG. **2** and identical to the circumferential direction.

In the inductively coupled plasma etching apparatus in accordance with the illustrative embodiment, a high frequency current supplied from the high frequency power supply unit **66** flows through each of component within the RF antenna **54**. As a result, high frequency AC magnetic fields distributed in loop shapes are formed around the inner coil **58**, the intermediate coil **60** and the outer coil **62** of the RF antenna **54** according to the Ampere's Law. Further, under the dielectric window **52**, magnetic force lines passing through the processing space in the radial direction are formed even in a relatively lower region.

In this case, a diametric directional (horizontal) component of a magnetic flux density in the processing space may be zero (0) constantly at a central region and a periphery of the processing chamber **10** regardless of a magnitude of the high frequency current. Further, the radial directional (horizontal) component of a magnetic flux density in the processing space may have a maximum value at a certain portion therebetween. A density distribution of the induced electric field in the azimuth direction generated by the AC magnetic field of the high frequency may have the same pattern as a magnetic flux density distribution in a diametrical direction. That is, an electron density distribution within the donut-shaped plasma in the diametrical direction may substantially correspond to a current split within the RF antenna **54** in a macro view.

The RF antenna **54** of the illustrative embodiment is different from a typical spiral coil wound from its center or inner peripheral end to an outer peripheral end thereof. That is, the RF antenna **54** includes the circular ring-shaped inner coil **58** localized to the central portion of the antenna; the circular ring-shaped intermediate coil **60** localized to the intermediate portion of the antenna; and the circular ring-shaped outer coil **62** localized to a peripheral portion of the antenna. A current split in the RF antenna **54** may be concentrated in the vicinities of each of the coils **58**, **60** and **62**.

Here, a high frequency current I_i (hereinafter, referred to as an "inner coil current") may be regular or uniform over the loop of the inner coil **58** and flows in the inner coil **58**. A high frequency current I_m (hereinafter, referred to as an "intermediate coil current") may be regular or uniform over the loop of the intermediate coil **60** and flows in the intermediate coil **60**. A high frequency current I_o (hereinafter, referred to as an "outer coil current") may be regular or uniform over the loop of the outer coil **62** and flows in the outer coil **62**.

Therefore, in the donut-shaped plasma generated below (inside) the dielectric window **52** of the processing chamber **10**, as shown in FIG. **3**), a current density (i.e. plasma density) may be remarkably increased (maximized) at positions right below the inner coil **58**, the intermediate coil **60** and the outer coil **62**. Thus, a current density distribution within the donut-shaped plasma may not be uniform in a

diametrical direction and may have an uneven profile. However, since the plasma is diffused in all directions within the processing space of the processing chamber **10**, a plasma density in a vicinity of the susceptor **12**, i.e. on the substrate W, may become very uniform.

In the present illustrative embodiment, the inner coil **58**, the intermediate coil **60** and the outer coil **62** have the circular ring shapes. Further, since a regular or uniform high frequency currents flow in the circumferential directions of the coils, a plasma density distribution can constantly be uniformized in the circumferential directions of the coils in the vicinity of the susceptor **12**, i.e., on the substrate W as well as within the donut-shaped plasma.

Further, in the radial direction, by varying and setting the electrostatic capacitances C_{86} and C_{88} of the intermediate capacitor **86** and the outer capacitor **88** to have appropriate values within certain ranges, it is possible to adjust a balance between the currents I_i, I_m and I_o flowing in the inner coil **58**, the intermediate coil **60** and the outer coil **62**, respectively. Accordingly, plasma density distribution within the donut-shaped plasma can be controlled as desired. Thus, plasma density distribution in the vicinity of the susceptor **12**, i.e., on the substrate W can be controlled as desired, and plasma density distribution can be easily uniformized with high accuracy.

In the illustrative embodiment, the wavelength effect and the voltage drop within the RF antenna **54** depend on a length of each of the coils **58**, **60**, **62**. Accordingly, by setting the length of each of the coils to prevent the wavelength effect from occurring in the coils **58**, **60**, **62**, both the wavelength effect and the voltage drop within the RF antenna **54** can be reduced. In order to prevent the wavelength effect, the length of each of the coils **58**, **60**, **62** is desirably shorter than a ¼ wavelength of the high frequency RF_H.

The condition that the length of each the coil is less than a ¼ wavelength of the high frequency RF_H is easily satisfied when a diameter of a coil is small, and the number of windings is small. Accordingly, in the RF antenna, the inner coil **58** having a smallest diameter can be easily subject to a configuration of a multiple number of windings. The outer coil **62** having a largest diameter is desirably subject to a single winding, rather than a multiple number of windings. The intermediate coil **60** depends on a diameter of the semiconductor wafer W, the frequency of the high frequency RF_H, and the like. However, the intermediate coil **60** is desirably subject to a single winding, like the outer coil **62**.

[Functions of Capacitors Added to the RF Antenna]

The core technical feature of the illustrative embodiment lies in that the RF antenna **54** is segmented in parallel in the diametrical direction into the three coils **58**, **60**, **62** having different coil diameters. Further, the variable intermediate capacitor **86** and the variable outer capacitor **88** are electrically connected in series to the intermediate coil **60** and the outer coil **62**, respectively. Meanwhile, any reactance device (in particular, a capacitor) is not connected to the inner coil **58**.

Here, as illustrated in FIG. **4**, it is assumed that no capacitor is connected to the RF antenna. In such case, more remarkable and stronger plasma than that generated directly under the intermediate coil **60** and the outer coil **62** is generated directly under the inner coil **58**. The reason that the remarkable and strong plasma is generated directly under the inner coil **58** will be described. A self-inductance L of a single circular ring-shaped coil is expressed by the formula (1) below, where a thickness (radius) of a coil conducting wire is represented as "a", and a coil diameter (radius) is represented as "r".

[Formula (1)]

$$L = r\mu_0\left(\log\frac{8r}{a} - 2\right) \quad (1)$$

Here, μ_o is a vacuum permeability, and the coil diameter (radius) r is a middle value between a radius of an inner periphery of a coil and a radius of an outer periphery of a coil.

From the formula (1), the self-inductance L is linearly proportional to the coil radius r. When a frequency of the high frequency is f, an impedance Z of the circular ring-shaped coil is 2πfL (Z=2πfL), and proportional to the self-inductance L. Accordingly, if the coil radiuses of the inner coil **58**, the intermediate coil **60**, and the outer coil **62** are, for example, about 50 mm, about 100 mm, and about 150 mm, respectively, the inner coil current I_i flows in the inner coil **58**, and an amount of the inner coil current I_i is approximately 2 times larger than the intermediate coil current I_m flowing in the intermediate coil **60**, and approximately 3 times larger than the outer coil current I_o flowing in the outer coil **62**. Density of the plasma generated by the circular ring-shaped coils is slightly lowered in efficiency when the radiuses of the coils are small. However, the plasma density generally depends on an amount of the coil currents, regardless of the radiuses of the coils. As such, several times stronger plasma than that generated directly under the intermediate coil **60** and the outer coil **62** is generated directly under the inner coil **58**. Accordingly, the plasma density distribution near the susceptor **12**, i.e., on the semiconductor wafer W has a profile, where the central portion in the diametrical direction is protruded and becomes high.

However, a coil has a positive reactance, and a capacitor has a negative reactance. When a capacitor is connected to a coil, the negative reactance of the capacitor removes the positive reactance of the coil. As a result, a combined reactance becomes lower than the reactance of the coil. Accordingly, increasing the amount of the inner coil current I_i by connecting a capacitor to the inner coil **58** does not have an effect on the uniformity of the plasma density distribution, and rather, results in a reverse effect thereon.

This is the same when the coils **58**, **60**, **62** are configured by spiral coils having N_i, N_m, and N_o turns, respectively. That is, since an inductance of each coil is proportional to the number of turns (the number of windings), an impedance of each coil is also proportional to the number of turns. Accordingly, a ratio of the coil currents (I_i, I_o) flowing in the inner coil **58** and the outer coil **62**, respectively, is $I_i{:}I_o=r_o{*}N_o{*}N_i{:}r_i{*}N_i{*}N_o=r_o{:}r_i$. Meanwhile, the plasma density (n_i, n_o) generated directly under each of the coils **58** and **62** is determined by multiplying the coil current and the number of turns. Accordingly, a ratio of the plasma densities (n_i, n_o) generated directly under the inner coil **58** and the outer coil **62** is $n_i{:}n_o=r_o{*}N_o{*}N_i{:}r_i{*}N_i{*}N_o=r_o{:}r_i$, which depends on a ratio of radiuses. The ratio of the coil currents and the plasma densities is identically applied to the case of the inner coil **58** and the intermediate coil **60**. As described, constantly, stronger plasma than those generated directly under the intermediate coil **60** and the outer coil **62** is generated directly under the inner coil **58**.

Actually, an impedance of a wiring from the output terminal of the matching unit **74** to the corresponding coil cannot be ignored. A length of the wiring is determined by a height from the output terminal of the matching unit **74** to the RF antenna **54**. Thus, it may be assumed that the length of the wiring is the same among the inner side, the intermediate side, and the outer side. Further, it is assumed that the wiring impedance is the same at the inner side, the intermediate side, and the outer side. In such case, if the outer coil **62** and the inner coil **58** have impedances of about 75Ω and about 25Ω, respectively, when the wiring impedance is approximately about 10Ω, $I_i:I_o=(75+10):(25+10)=85:35=2.41:1$. Thus, there is still a difference two or more times between the impedances of the coils and the wiring impedance.

When a pressure is relatively high (generally, more than about 100 mTorr), and thus, plasma is difficult to be diffused, the above-described balance is achieved at the inner side and the outer side. However, when a pressure is lowered, and thus, the plasma is easy to be diffused, a plasma density at a central portion is further protruded and becomes high.

Accordingly, there is established a theory providing that under any conditions, a plasma density directly under an innermost coil, among a multiple number of coils electrically connected in parallel to one another and having different diameters, becomes relatively high.

In the illustrative embodiment, based on the above-described theory, no capacitor is added (connected) to the inner coil **58** between the both terminals (between the first node N_A and the second node N_B) of the RF antenna **54**. The variable capacitors **86**, **88** are connected in series to the intermediate coil **60** and the outer coil **62**, respectively. By adjusting the electrostatic capacitances C_{86}, C_{88} of the variable capacitors **86**, **88** in consideration of reducing a combined reactance, the amounts of the coil currents I_m, I_o flowing in the intermediate coil **60** and the outer coil **62**, respectively, are properly increased. In this manner, it is possible to conform the coil currents I_i, I_m, I_o to be in substantially the same amounts. Alternatively, it is possible to make the intermediate coil current I_m and/or the outer coil current I_o larger than the inner coil current I_i. Here, the increasing amounts of the coil currents I_m, I_o by the variable capacitors **86**, **88** flow in the intermediate coil **60** and the outer coil **62**, and contribute to the plasma generation. Thus, no waste of high frequency power is generated.

In general, in order to correct the profile, where a plasma density is protruded and becomes high at the central portion of the diametrical direction, it is effective to adjust a ratio (balance) of the inner coil current I_i flowing in the inner coil **58** and the outer coil current I_o, flowing in the outer coil **62**. In the illustrative embodiment, a ratio of the coil currents I_i, I_o can be adjusted simply by varying the electrostatic capacitance C_{88} of the outer capacitor **88**.

In this case, in order to uniformize the plasma density distribution under various conditions, it is desirable to set a variable range of multiplication (I_o*n_o) of the outer coil current I_o and the number of turns n_o of the outer coil **62** to have a lower limit value smaller than and an upper limit value larger than multiplication (I_i*n_i) of the inner coil current I_i and the number of turns n_i of the inner coil **58**. The ratio of the inner coil current I_i and the outer coil current I_o is proportional to a ratio of reciprocal numbers of an impedance of the inner coil **58** (hereinafter, referred to as an "inner impedance") and a combined impedance of the outer coil **62** and the outer capacitor **88** (hereinafter, referred to as an "outer combined impedance"). Accordingly, if the inner impedance (fixed value) is represented as Z_i, and minimum and maximum values for the outer combined impedance (variable value) are represented as $Z_o(_{min})$ and $Z_o(_{max})$, respectively, the above-described condition for a multiplication of the coil current and the number of turns is expressed as follows:

[Formula (2)]

$$|N_o/Z_{o(max)}|<|N_i/Z_i|<|N_o/Z_{o(min)}| \quad (2)$$

Further, the inner impedance Z_i and the outer combined impedance Z_o depend on their respective average coil radiuses, except for the electric connecting portion. An effect of the electric connecting portion cannot be ignored, but is not dominant. Thus, the above-described condition may be expressed as follows:

[Formula (3)]

$$\frac{1}{2\pi fr_o\mu_0\left(\log\frac{8r_o}{a}-2\right)-\frac{1}{2\pi fN_oC_{o(max)}}}<\frac{1}{2\pi fr_i\mu_0\left(\log\frac{8r_i}{a}-2\right)}<\frac{1}{2\pi fr_o\mu_0\left(\log\frac{8r_o}{a}-2\right)-\frac{1}{2\pi fN_oC_{o(min)}}} \quad (3)$$

Here, $C_o(_{min})$ is a value of the electrostatic capacitance C_{88} of the outer capacitor **88** when the outer combined impedance Z_o is minimum within an adjustable range. $C_o(_{max})$ is a value of the electrostatic capacitance C_{88} of the outer capacitor **88** when the outer combined impedance Z_o is maximum. $C_o(_{min})$ and $C_o(_{max})$ may not be the same as the minimum value and the maximum value of the variable range. The outer combined impedance Z_o becomes minimum, when the outer coil **62** and the outer capacitor **88** cause a series resonance. $C_o(_{min})$ is a value of the electrostatic capacitance C_{88} of the outer capacitor **88** at that time. The outer combined impedance Z_o becomes maximum, when the electrostatic capacitance C_{88} of the outer capacitor **88** becomes apart from the series resonance point up to an upper or lower limit of the variable range. $C_o(_{max})$ is a value of the electrostatic capacitance C_{88} of the outer capacitor **88** at that time.

As described, no capacitor is connected to the inner coil **58**, and the outer capacitor **88** is connected in series to the outer coil **62**. By varying the electrostatic capacitance C_{88} of the outer capacitor **88**, the ratio of the inner coil current I_i and the outer coil current I_o is properly adjusted. Also, a general profile of the plasma density distribution within the donut-shaped plasma generated directly under the RF antenna **54** (in particular, balance between the central portion and the peripheral portion) can be properly controlled.

In the illustrative embodiment, the intermediate coil **60** is arranged between the inner coil **58** and the outer coil **62**. The variable intermediate capacitor **86** is connected in series to the intermediate coil **60**. This configuration is intended to minutely control the plasma density distribution (in particular, at the intermediate portion) within the donut-shaped plasma. The configuration is useful when generating plasma under a low pressure or generating plasma of a large diameter.

Instead of providing the intermediate coil **60**, it is considered to form the outer coil **62** in a spiral shape to cover the area of the intermediate portion of the antenna **54** with the outer coil **62**. In this case, however, the same coil current I_o flows in all sections of the outer coil **62**. Thus, the plasma density directly under the intermediate portion of the

antenna may become relatively high. It becomes difficult to achieve a uniform profile, for example, in the diametrical direction.

In actual processes, there is a case where a desirable profile (e.g., flat) in the whole diametrical direction is obtained by forcibly reducing the plasma density within the donut-shaped plasma directly under the intermediate portion of the antenna. In particular, this situation easily occurs when an amount of the outer coil current I_o is rapidly increased in order to raise peripheral plasma density to a desired level.

In this case, the intermediate capacitor **86** is used effectively. That is, the electrostatic capacitance C_{86} of the intermediate capacitor **86** is varied in a range lower than a value of a series resonance point. As a result, a combined reactance of the intermediate coil **60** and the intermediate capacitor **86** (hereinafter, referred to as an "intermediate combined reactance") becomes a negative value. Accordingly, the intermediate coil current I_m flows in a direction opposite to the circumferential direction and in a certain current amount (in particular, it is also possible to slightly increase the current amount from the state of substantially zero (0)). Accordingly, the plasma density within the donut-shaped plasma directly under the intermediate coil can be locally and easily controlled. Furthermore, the plasma density distribution in the whole diametrical direction near the susceptor **12**, i.e., on the semiconductor wafer W can be easily controlled.

The function of the intermediate capacitor **86** has been verified by the experiment shown in FIGS. **5**A and **5**B. In the experiment, as illustrated in FIG. **5**A, the inner coil **58** of the RF antenna **54** is formed with two windings (2 turns) having a diameter of about 100 mm. The intermediate coil **60** and the outer coil **62** are formed with a single winding (single turn) having diameters of about 200 mm and about 300 mm, respectively. As primary process conditions, the frequency of the high frequency RF_H is about 13.56 MHz, the RF power is about 1500 W, a pressure in the processing chamber **10** is about 100 mTorr, the processing gas is a mixture gas of Ar and O_2, and a flow rate of the processing gas is Ar/O_2=about 300/30 sccm.

In the experiment, the electrostatic capacitance C_{88} of the outer capacitor **88** is fixed at about 560 pF. The electrostatic capacitance C_{86} of the intermediate capacitor **86** is varied to about 13 pF, to about 40 pF, and to about 64 pF. In this case, it is confirmed that as shown in FIG. **5**B, the intermediate coil current I_m is changed to about −0.4 A, to about −5.0 A, and to about −11.2 A, and the electron density N_e (i.e., plasma density) near a portion directly under the intermediate coil **60** can be locally and properly lowered. When C_{86} is about 13 pF, the inner and outer coil currents I_i, I_o are about 16.4 A and about 18.3 A, respectively. When C_{86} is about 40 pF, the inner and outer coil currents I_i, I_o are about 17.4 A and about 19.4 A, respectively. When C_{86} is about 64 pF, the inner and outer coil currents I_i, I_o are about 19.0 A and about 20.1 A, respectively. If an amount of the intermediate coil current I_m flowing in the opposite direction increases, amounts of the inner coil current I_i and the outer coil current I_o, which flow in the forward direction, slightly increase. However, a ratio (balance) of the coil currents I_i, I_o usually does not vary.

With respect to other functions in the RF antenna **54** of the present illustrative embodiment, it is possible to vary the electrostatic capacitance C_{88} of the outer capacitor **88** in a range lower than the value of the series resonance point. As a result, a combined reactance of the outer coil **62** and the outer capacitor **88** (hereinafter, referred to as an "outer combined reactance") becomes a negative value. Accordingly, it is possible to make the outer coil current I_o flow in the opposite direction. For example, if plasma diffuses excessively toward the outer side of the diametrical direction within the processing chamber **10**, the inner wall of the processing chamber **10** may be easily damaged. In such case, it is possible to make the coil current I_o flow in a direction opposite to the outer coil **62**, thereby confining the plasma in the inner side of the outer coil **62**. As a result, the damage of the inner wall in the processing chamber **10** can be prevented. This function is effective, for example, when a multiple number of intermediate coils **60** having different coil diameters are arranged while being spaced from one another in the diametrical direction, or when the outer coil **62** is arranged at a further outer side of the diametrical direction than the susceptor **12**.

In the illustrative embodiment, by making at least one of the electrostatic capacitances C_{86}, C_{88} of the intermediate capacitor **86** and the outer capacitor **88** close to a value when a series resonance is generated, it is possible to reduce the inner coil current I_i flowing in the inner coil **58**. By making at least one of the electrostatic capacitances C_{86}, C_{88} of the intermediate capacitor **86** and the outer capacitor **88** apart from the value when the series resonance is generated, it is possible to increase the inner coil current I_i. That is, the inner coil current I_i, the intermediate coil current I_m, and the outer coil current I_o are in a ratio of $I_i:I_m:I_o=(1/Z_i):(1/Z_m):(1/Z_o)$. Accordingly, as C_{86} and/or C_{88} are close to the value when the series resonance is generated, Z_m and/or Z_o become smaller values. Here, I_m and/or I_o are relatively increased, and I_i becomes smaller. Meanwhile, as C_{86} and/or C_{88} are apart from the value when the series resonance is generated, Z_m and/or Z_o become large values. Here, I_m and/or I_o are relatively decreased, and I_i becomes larger.

[Another Testing Example or a Modified Example for the RF Antenna]

In the illustrative embodiment, in controlling (in particular, uniformizing) the plasma density distribution, no capacitor is connected to the inner coil **58**, considering that an amount of the inner coil current I_i does not need to be varied in order to increase the current amount thereof.

However, there is a case where positively or forcibly controlling an amount of the inner coil current I_i is effective. For example, when a pressure in the processing chamber **10** is low, the plasma tends to be gathered at a central portion of the diametrical direction. As described above, this problem may be resolved by varying the electrostatic capacitance C_{88} of the outer capacitor **88** and adjusting a ratio of the inner coil current I_i and the outer coil current I_o. However, the problem may not be completely resolved.

As illustrated in FIGS. **6**A and **6**B, the fixed or semi-fixed inner capacitor **104** is electrically connected in series to the inner coil **58** between the first node N_A and the second node N_B in the RF antenna **54**. In this configuration, it is also possible to select or adjust the electrostatic capacitance C_{104} of the inner capacitor **104** to be a desired value. As a result, a combined reactance X_i of the inner coil **58** and the inner capacitor **104** (hereinafter, referred to as an "inner combined reactance") becomes a desired value. When the fixed or semi-fixed capacitor **104** and the variable outer capacitor **88** are provided, the condition formulas (2) and (3) are also applied with respect to the number of turns of each of the coils or the variable control of the electrostatic capacitance C_{88} of the outer capacitor **88**.

Although a freedom degree or an accuracy of the plasma density distribution control is somewhat decreased, in order to reduce costs, a variable capacitor for the inner capacitor

104 and a fixed or semi-fixed capacitor for the outer capacitor **88** may be used, as illustrated in FIGS. **7**A and **7**B. Although not illustrated herein, a fixed or semi-fixed capacitor for the intermediate capacitor **86** may be used. Further, the intermediate capacitor **86** may be omitted.

When the fixed or semi-fixed outer capacitor **88** and the variable inner capacitor **104** are provided, in uniformizing the plasma density distribution under various conditions, it is desirable to set a variable range of multiplication (I_i*n_i) of the inner coil current I_i and the number of turns n_i of the inner coil **58** to have a lower limit value smaller and an upper limit value larger than multiplication (I_o*n_o) of the outer coil current I_o and the number of turns (n_o) of the outer coil **62**. The ratio of the inner coil current I_i and the outer coil current I_o is proportional to a ratio of reciprocal numbers of the combined impedance (inner combined impedance) of the inner coil **58** and the inner capacitor **104**, and the combined impedance (outer combined impedance) of the outer coil **62** and the outer capacitor **88**. Accordingly, if the outer impedance (fixed value) is represented as Z_o, and minimum and maximum values of the inner combined impedance (variable value) are represented as $Z_i(_{min})$ and $Z_i(_{max})$, respectively, the above-described condition for the multiplication of the coil current and the number of turns is expressed as follows:

[Formula (**4**)]

$$|N_i/Z_{i(max)}|<|N_o/Z_o|<|N_i/Z_{i(min)}| \quad (4)$$

The inner combined impedance Z_i and the outer combined impedance Z_o depend on their respective average coil radiuses, except for the electric connecting portion. An effect of the electric connecting portion cannot be ignored, but is not dominant. Thus, the above-described condition may be expressed as follows:

[Formula (5)]

$$\frac{1}{2\pi fr_i\mu_0\left(\log\frac{8r_i}{a}-2\right)-\frac{1}{2\pi fN_iC_{i(max)}}} < \frac{1}{2\pi fr_0\mu_0\left(\log\frac{8r_0}{a}-2\right)} < \frac{1}{2\pi fr_i\mu_0\left(\log\frac{8r_i}{a}-2\right)-\frac{1}{2\pi fN_iC_{i(min)}}} \quad (5)$$

Here, $C_i(_{min})$ is a value of the electrostatic capacitance C_{104} of the inner capacitor **104** when the inner combined impedance Z_i is minimum within an adjustable range. $C_i(_{max})$ is a value of the electrostatic capacitance C_{104} of the inner capacitor **104** when the inner combined impedance Z_i is maximum. $C_i(_{min})$ and $C_i(_{max})$ may not be the same as a minimum value and a maximum value of the variable range of C_{104}. The inner combined impedance Z_i becomes minimum, when the inner coil **58** and the inner capacitor **104** cause a series resonance. $C_i(_{min})$ is a value of the electrostatic capacitance C_{104} of the inner capacitor **104** at that time. Further, the inner combined impedance Z_i becomes maximum, when the electrostatic capacitance C_{104} of the inner capacitor **104** becomes apart from the series resonance point up to an upper or lower limit of the variable range. $C_i(_{max})$ is a value of the electrostatic capacitance C_{104} of the inner capacitor **104** at that time.

The variable inner capacitor **104** is connected to the inner coil **58**, and a fixed or semi-fixed outer capacitor **88** is connected in series to the outer coil **62**. By varying the electrostatic capacitance C_{104} of the inner capacitor **104**, the ratio of the inner coil current I_i and the outer coil current I_o is properly adjusted. Also, it is possible to properly control a profile of the plasma density distribution within the donut-shaped plasma generated directly under the RF antenna **54** (in particular, a balance of the central portion and the peripheral portion).

In accordance with a modified example, in order to positively or forcibly reduce the amount of the inner coil current I_i, a variable inductor **106** may be electrically connected in series to the inner coil **58** between the first node N_A and the second node N_B. Also, it is possible to substitute the intermediate capacitor **86** with another variable inductor, or it is possible to omit the outer capacitor **88** for reducing costs.

The loop shape of each of the coils **58**, **60**, **62** in the RF antenna **54** is not limited to a circular shape. For example, as illustrated in FIG. **9**, the loop shape of each of the coils **58**, **60**, **62** may be square according to the shape of the target object to be processed. When the loop shape of each of the coils **58**, **60**, **62** is polygonal, the variable intermediate capacitor **86** and the outer capacitor **88** may be electrically connected in series to the intermediate coil **60** and the outer coil **62**, respectively, and no capacitor may be connected to the inner coil **58**.

An inductance L of a rectangular coil, where lengths of two sides are represented as "a" and "b", and a thickness of the coil is represented as a radius "d", is expressed by the formula (6) below.

[Formula (6)]

$$L=\frac{\mu_0}{\pi}\left\{-a\log\left(a+\sqrt{a^2+b^2}\right)-b\log\left(b+\sqrt{a^2+b^2}\right)+(a+b)\log\frac{2ab}{d}+2\sqrt{a^2+b^2}-\frac{7}{4}(a+b)\right\} \quad (6)$$

As shown from the formula (6), the inductance L of the rectangular coil is substantially proportional to the lengths of the two sides "a", "b". Accordingly, even when no capacitor is connected to the inner coil **58** as the same as in the circular coil, the plasma density distribution can be simply or easily controlled by the intermediate capacitor **86** and the outer capacitor **88**.

FIG. **10** shows an example where the coils (inner coil **58**/intermediate coil **60**/outer coil **62**) of the RF antenna **54** are formed with a pair of spiral coils. The coils are arranged in a spatially and electrically parallel. The spiral coils may be used unless the wavelength effect is really a problem.

In the illustrated configuration example, the inner coil **58** is formed with a pair of spiral coils **58***a*, **58***b* having a multiple number of turns (respectively, 2 turns in the illustrated example) and being deviated 180° from the circumferential direction. The spiral coils **58***a*, **58***b* are electrically connected in parallel between a node N_C provided at a downstream side lower than the node N_A of the high frequency power supply **72** and a node N_D provided at an upstream side higher than the node N_B of the earth line **70**.

The intermediate coil **60** is formed with a pair of spiral coils **60***a*, **60***b* each having a multiple number of turns (respectively, 2 turns in the illustrated example) and being deviated 180° from the circumferential direction. The spiral coils **60***a*, **60***b* are electrically connected in parallel between a node N_E provided at a downstream side lower than the node N_A of the high frequency power supply **72** and a node N_F provided at an upstream side higher than the node N_B (and the intermediate capacitor **86**) of the earth line **70**.

The outer coil **62** is formed with a pair of spiral coils **62***a*, **62***b* each having a multiple number of turns (respectively, 2

turns in the illustrated example) and being deviated 180° from the circumferential direction. The spiral coils **62***a*, **62***b* are electrically connected in parallel between a node N_G provided at a downstream side lower than the node N_A of the high frequency power supply **72** and a node N_H provided at an upstream side higher than the node N_B (and the outer capacitor **88**) of the earth line **70**.

When the inner coil **58**, the intermediate coil **60**, and the outer coil **62** are segmented into k_i, k_m, and k_o spiral coils in parallel, respectively, if no capacitor is connected to the RF antenna **54**, a ratio of plasma densities n_i, n_m, n_o, which is generated directly under the coils **58**, **60**,**62**, respectively, is expressed by an approximation equation (3) below.

$$n_i:n_m:n_o \approx (k_i/r_i):(k_m/r_i):(k_o/r_i):(k_o/r_i) \quad (3)$$

As in the illustrated example, if the number of segments k_i, k_m, k_o is the same (2 segments), the plasma density generated directly under the inner coil **58**, i.e., the plasma in the central portion becomes relatively higher. In this case, the most desirable configuration is that no capacitor is connected to the inner coil **58**, and the variable intermediate capacitor **86** and the outer capacitor **88** are connected in series to the intermediate coil **60** and the outer coil **62**, respectively.

With respect to another modified example, as illustrated in FIG. **11**, it is possible to connect an intermediate capacitor **86** and an outer capacitor **88** between the first node N_A of the high frequency power supply **72** and the RF inlet terminals **60***in*, **62***in* of the intermediate coil **60** and the outer coil **62**. Connecting a capacitor or an inductor for adjusting impedance between the first node N_A and each of the coils may be applied to another experimental example or another modified example (FIGS. **6**A, **8**, **9**, and **10**).

FIG. **12** illustrates the configuration where an output common capacitor **108** is connected between the second node N_B and the earth line **70** (or on the earth line **70**) at the terminal end of the RF antenna **54**, and electrically connected in series to all the coils **58**, **60**, **62** of the RF antenna **54**. The output terminal (terminal end) common capacitor **108** may be a common fixed capacitor or a variable capacitor.

The output terminal (terminal end) common capacitor **108** has a function of adjusting the whole impedance of the RF antenna **54**, and a function of suppressing ion sputter performed on the ceiling plate or the dielectric window **52** by serially raising the whole potential of the RF antenna **54** from a ground potential.

Although not illustrated herein, it is possible to provide other coils at the diametrical direction inner side of the inner coil **58** and/or the diametrical direction outer side of the outer coil **62** in the RF antenna **54**. As a result, total 4 or more coils are arranged in the diametrical direction at intervals while being electrically connected in parallel to one another.

In the above-described embodiment, the illustrated configuration of the inductively coupled plasma etching apparatus is nothing more than an example. Not only each component of the plasma generating mechanism but also each component which is not directly relevant to plasma generation can be modified in various manners.

By way of example, the basic shape of the RF antenna may be a dome shape besides the planar shape mentioned above. Further, it may be also possible to have configuration in which a processing gas is introduced into the chamber **10** from the processing gas supply unit through a ceiling. Furthermore, it may be also possible not to apply a high frequency power RF_L for DC bias control to the susceptor **12**.

The inductively coupled plasma processing apparatus or the inductively coupled plasma processing method of the present disclosure can be applied to, not limited to a plasma etching technology, other plasma processes such as plasma CVD, plasma oxidation, plasma nitridation, and sputtering. Further, the target substrate in the present disclosure may include, but is not limited to a semiconductor wafer, various kinds of substrates for a flat panel display or photo mask, a CD substrate, and a print substrate.

What is claimed is:

1. A plasma processing method for performing a plasma process on a processing target substrate by using a plasma processing apparatus having a processing chamber having a dielectric window; a substrate holding unit for holding thereon a processing target substrate within the processing chamber; a processing gas supply unit configured to supply a processing gas into the processing chamber in order to perform a plasma process on the processing target substrate; an RF antenna provided outside the dielectric window in order to generate plasma of the processing gas within the processing chamber by inductive coupling; and a high frequency power supply unit configured to supply a high frequency power having a frequency for generating a high frequency electric discharge of the processing gas in the RF antenna, the plasma processing method comprising:

segmenting the RF antenna into an inner coil, an intermediate coil, and an outer coil with gaps therebetween in a radial direction, respectively, the inner coil, the intermediate coil and the outer coil being electrically connected to one another in parallel between a first node and a second node provided in high frequency transmission lines of the high frequency power supply unit;

providing a variable intermediate capacitor and a variable outer capacitor between the first node and the second node, the variable intermediate capacitor being electrically connected in series to the intermediate coil, the variable outer capacitor being electrically connected in series to the outer coil, no reactance device being connected to the inner coil; and

controlling plasma density distribution on the processing target substrate by selecting or variably adjusting electrostatic capacitances of the variable intermediate capacitor and the variable outer capacitor such that increased amounts of coil currents by the variable intermediate capacitor and the variable outer capacitor flow only in the intermediate coil and the outer coil,

wherein when the number of windings of the inner coil and the number of windings of the outer coil are N_i and N_o, respectively, an impedance of the inner coil is Z_i, and a maximum value and a minimum value of a combined impedance of the outer coil and the outer capacitor obtained by varying an electrostatic capacitance of the outer capacitor are $Z_o(_{max})$ and $Z_o(_{min})$, respectively, the following equation is established:

$$|N_o/Z_{o(max)}|<|N_i/Z_i|<|N_o/Z_{o(min)}|.$$

2. The plasma processing method of claim **1**,

wherein the current flowing in the inner coil is reduced by making at least one of electrostatic capacitances of the intermediate capacitor and the outer capacitor close to a value when a series resonance is generated.

3. The plasma processing method of claim **1**,
wherein the current flowing in the inner coil is increased by making at least one of electrostatic capacitances of the intermediate capacitor and the outer capacitor apart from a value when a series resonance is generated.

4. The plasma processing method of claim **1**,
wherein electrostatic capacitances of the intermediate capacitor and the outer capacitor are adjusted to enable plasma density on the processing target substrate to be uniformized in a diametrical direction.

5. The plasma processing method of claim **1**,
wherein the plasma density on the processing target substrate is adjusted so as to be uniformized in the diametrical direction by conforming multiplication of the number of turns of each of the intermediate coil and the outer coil and an amount of a coil current thereof to multiplication of the number of turns of the inner coil and an amount of a coil current thereof.

6. The plasma processing method of claim **1**,
wherein a direction of the current flowing in the intermediate coil is opposite to a direction of the current flowing in the inner coil in the circumferential direction by variably adjusting the electrostatic capacitance of the intermediate capacitor in a range smaller than a value when the intermediate capacitor and the intermediate coil generate a series resonance.

7. The plasma processing method of claim **1**,
wherein a direction of the current flowing in the intermediate coil is identical to a direction of the current flowing in the inner coil in the circumferential direction by variably adjusting the electrostatic capacitance of the intermediate capacitor in a range larger than a value when the intermediate capacitor and the intermediate coil generate a series resonance.

8. The plasma processing method of claim **1**,
wherein a direction of the current flowing in the outer coil is opposite to a direction of the current flowing in the inner coil in the circumferential direction by variably adjusting the electrostatic capacitance of the outer capacitor in a range smaller than a value when the outer capacitor and the outer coil generate a series resonance.

9. The plasma processing method of claim **1**,
wherein a direction of the current flowing in the outer coil is identical to a direction of the current flowing in the inner coil in the circumferential direction by variably adjusting the electrostatic capacitance of the outer capacitor in a range larger than a value when the outer capacitor and the outer coil generate a series resonance.

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